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WAVE-LENGTHS OF CARBON, OXYGEN, AND NITROGEN IN THE EXTREME ULTRA-VIOLET WITH A CONCAVE GRATING AT GRAZING INCIDENCE

By J. BARTON HOAG

ABSTRACT

A *vacuum spectrograph* has been constructed with use of a *concave speculum grating* of 215.3-cm radius having 591 lines per millimeter. The familiar *Rowland mounting* is used except that the *slit* is *placed close to the grating*, making the angle of incidence approximately 80°. This results in high dispersion and resolving power. In the first order the scale varies from 3.64 A per millimeter at 1700 A to 2.0 A per millimeter at 300 A. *Wave-lengths* for spark discharge through *magnesium* and *carbon electrodes are given* from 1658 to 558 A. By flowing gases through the electrodes during the sparking, *simultaneous gaseous and metallic spectra are obtained.*

INTRODUCTION

The vacuum spectrographs ordinarily used for obtaining spectra in the extreme ultra-violet have been constructed so that the light from the slit reaches the grating at nearly normal incidence and is diffracted to the plate-holder located near the slit. The success of A. H. Compton and R. Doan[1] in making a direct determination of the wave-length of X-rays, by the use of large angles of incidence of the beam and a plane grating, suggested that a similar arrangement might be used for exploring the extreme ultra-violet, particularly in the region of very short wave-lengths.

DESIGN

A vacuum spectrograph was constructed as shown in Figure 1, which is drawn to scale. The source of light, the slit, concave grating,

[1] *Proceedings of the National Academy of Sciences*, **11**, 598, 1925.

and plate-holder are all located on a circle whose radius of curvature is one-half that of the grating. The image of the slit is then sharply focused along this circle. This would be a typical Rowland mounting if the slit were not so close to the grating, i.e., the angle of incidence so large. In designing the apparatus the usual equation

$$m\lambda = d(\sin i - \sin \beta)$$

was used to compute the angle of diffraction (β) for the various wave-lengths (λ). The incident angle (i) was chosen as 80°. The grating available had 591 lines per millimeter and a radius of curvature of 215.3 cm. From this and the geometry of the figure the inclosing brass tube was chosen of such size as to cover a range of wave-lengths from 0 to 1700 A spread out over 70 cm. (The region from 0 to 200 A covers 12 cm). J. Thibaud[1] has also tried the large-angle spectrograph but used a plane grating, his spectra from 0 to 3000 A extending only over 4.2 cm.

Similarly the dispersion, or rather the scale (angstroms per millimeter along the film), was calculated and found to be very great, having the same value at 740 A as that of a 21-foot concave grating in a Rowland mounting in the first order. This scale is not constant but varies with the wave-length (λ) according to the relation

$$s = \sqrt{a + b\lambda + c\lambda^2},$$

where a, b, and c are constants of the apparatus. The values found experimentally, for the first order, are given roughly as follows:

Angstroms	Angstroms/mm
1700	3.64
1300	3.24
1000	2.96
800	2.70
500	2.30
300	2.0

EXPERIMENTAL

Several novel features were used in the construction of the apparatus. The source and slit in the side tube, the grating, and a base

[1] *Le journal de physique et le radium*, **8**, 13, 1927.

plate reaching the full length of the main body of the spectrograph were rigidly fixed to a short section of the main tube and could be removed from it as a unit (Fig. 1). The addition of a section to the far end of the base plate allowed the plate-holder to be used in the visible part of the spectrum. Also with use of the zero image, the apparatus could thus be adjusted in air—a great advantage over an alignment made in the vacuum chamber.

The plate-holder, which covers approximately one-third of the total range, was mounted in vertical ways and could be raised by means of an electromagnet and gears so that several exposures could

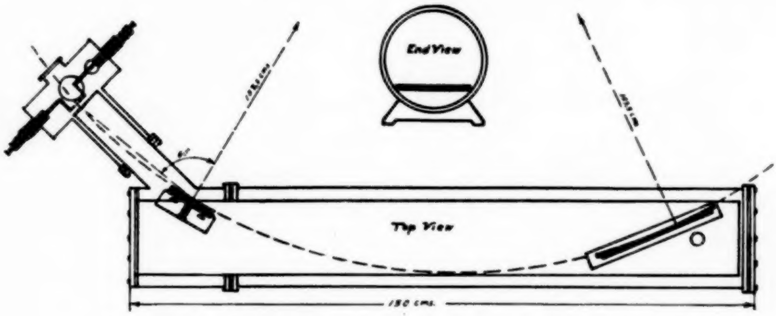


FIG. 1.—Vacuum spectrograph using large angle of incidence

be made on the same film without removing it from the vacuum. Two slightly tapered pins and a screw in the base of the holder, fitting into carefully located holes in the main base plate, allowed it to be quickly placed and clamped in any one of its positions. This, and the introduction of the films, was accomplished by removing the end plate the more distant from the grating. Paranite rubber (sulphur free) was used for all gaskets.

Films were made according to the specifications given by Schumann[1] except that only half as much gelatin was used. Films made by Hilger and Company were also used. The two were quite comparable. They were all made on extra heavy celluloid (1.35 mm thick). When lines were first obtained they were found to be curved, but this was due to a slight bulging of the film and was eliminated by clamping the films more firmly in the holder.

[1] Baly, *Spectroscopy*, p. 375, 1912.

The "hot spark"[1] was used as a source. The secondary voltage was 40,000, the capacity from 0.008 to 0.032 microfarad, the external spark gap from 0.1 to 1.5 cm, the internal gap (source) always less than 1 mm. The primary current of the transformer was 35 amp (110 volts), and was automatically made and broken twenty-three times each minute, the sparks lasting one-third to one-half second each. Considerable trouble was experienced in breaking these heavy currents until large copper terminals were used in transformer oil. The hot spark was observed through two windows in the source chamber. The total exposure times including the time for pumping out the gases given out during the spark were rarely greater than one hour, usually fifteen minutes, and occasionally only three minutes.

Various gases were flowed through the electrodes in the spark chamber during several of the exposures. The oxygen was removed from tank hydrogen and nitrogen by passing them over hot-copper shavings and phosphorous pentoxide. Tank helium and oxygen were passed over hot-copper oxide and phosphorous pent-oxide. Two brass-needle valves in series were used to admit the gases to the electrode. The needle of the second valve was fastened to an iron plunger fitting into an electromagnet so that a small quantity of gas from the first valve could be admitted suddenly into the chamber just as the spark occurred. The continued operation of the pumps (and the small volume of the source chamber) cleared out this gas between alternate sparks, and, at times, between successive sparks.

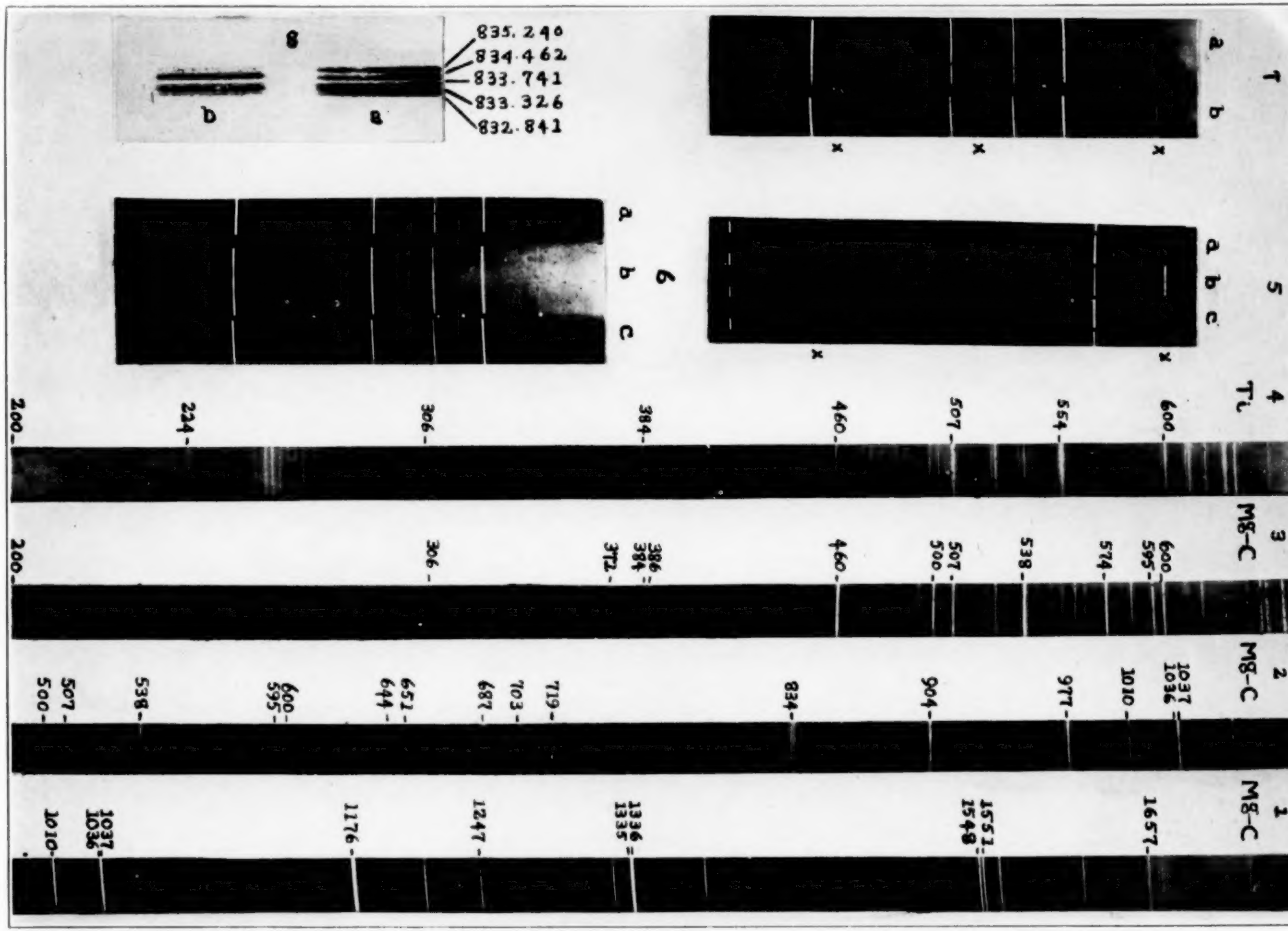
RESULTS

Various spectra have been photographed from 200 to 1650 A. The lower limit is interesting since the grating was originally ruled for work in the visible. The accompanying titanium spectrum shows lines clearly at 224 A, and the original negative shows several more extending to 200 A. None of the lines above the first order were observed, but it is hoped that a suitable grating will soon be available.

As can be seen by the enlargement of the 834 oxygen line (Plate VI, No. 8), the resolving power is such as to separate lines 0.4 A

[1] I. S. Bowen, *Journal of the Optical Society of America*, **13**, 89, 1926.

PLATE VI



Spectra of Carbon, Oxygen, and Nitrogen in Extreme Ultra-Violet

TABLE I

MAGNESIUM-CARBON ELECTRODES

Int.	I.A. Vac.	Accuracy	Int.	I.A. Vac.	Accuracy
2	1658.02*C*	2*S*	3	989.803*N*	*S*
4	1657.19*C*	2*S*	1	988.54	*B*
2	1656.27*C*	*S*	0	979.83	*B*
1	1623.83	*C*	9	977.031*C*	*S*
4	1614.47	*C*	1	944.66	*A*
1	1611.49	*C*	1	937.46	*C*
3	1577.57	*A*	0	933.48	*A*
5	1561.381*C*	*S*	3	916.698*N*	*S*
4	1560.463*C*	2*S*	2	915.990*N*	2*S*
5	1550.774	*S*	2	915.603*N*	*S*
6	1548.189	*S*	15	904.046*C*	4*S*
1	1544.92	*B*	1	898.87	*B*
1	1463.67	*C*	2	884.60	*B*
2	1431.8	....	0	860.44	*B*
2	1393.66	*A*	6	858.324*C*	2*S*
4	1378.73	*C*	1	854.83	*B*
4	1362.43	*A*	0	852.13	*B*
10	1335.705*C*	*S*	0	849.25	*B*
10	1334.539*C*	*S*	10	835.240*O*	2*S*
3	1329.204*C*	2*S*	10	834.462*O*	*S*
7	1323.84	*A*	9	833.741*O*	*S*
1	1304.83	*A*	9	833.326*O*	*S*
2	1302.3	....	9	832.841*O*	2*S*
1	1280.5	....	1	815.96	*B*
1	1268.93	*B*	4	809.67	*A*
1	1261.25	*B*	1	808.73	*B*
6	1247.391*C*	*S*	6	806.58	*B*
0	1230.0	....	0	803.51	*B*
4	1215.55	*A*	4	799.71	*B*
20	1175.644*C*	6*S*	7	796.665*O*	*S*
1	1158.75	*A*	6	790.205*O*	*S*
2	1152.23	*C*	5	787.716*O*	*S*
0	1148.6	....	4	786.47	*B*
1	1141.61*C*	*S*	3	779.824*O*	*S*
1	1139.1	....	1	753.75	*C*
1	1115.2	....	3	750.29	*B*
1	1085.650*N*	2*S*	2	748.43	*B*
1	1084.274*N*	2*S*	0	744.87	*C*
1	1077.1	....	0	728.56	*B*
4	1076.30	*C*	0	725.71	*B*
1	1072.9	....	0	721.55	*C*
6	1065.97	*C*	8	718.532*O*	2*S*
1	1062.59	*C*	0	716.86	*C*
2	1051.72	*B*	2	710.81	*A*
10	1037.021*C*	*S*	1	707.23	*B*
10	1036.336*C*	*S*	1	706.24	*B*
2	1025.71	*A*	7	703.853*O*	*S*
1	1021.28	*B*	7	702.858*O*	2*S*
1	1016.52	*A*	6	702.327*O*	*S*
1	1015.49	*B*	1	700.09	*B*
10	1010.070*C*	3*S*	1	698.73	*B*
2	999.33	*C*	0	696.56	*B*
3	991.571*N*	*S*	3	690.51	*B*

TABLE I—*Continued*

Int.	I.A. Vac.	Accuracy	Int.	I.A. Vac.	Accuracy
6	687.202*C*	2*S*	3	608.390*O*	*S*
6	685.669*N*	4*S*	2	600.583*O*	*S*
2	680.67	*B*	8	599.600*O*	*S*
3	661.49	*C*	3	597.82*O*	*S*
2	657.38	*C*	5	594.90*C*	2*S*
5	651.33	*B*	5	585.43	*B*
5	644.159*O*	*S*	4	580.975*O*	*S*
3	641.83	*B*	3	580.409*O*	*S*
4	625.848*O*	*S*	6	574.31	*B*
4	625.126*O*	*S*	3	560.52	*B*
3	624.609*O*	*S*	3	558.07	*B*
5	617.064*O*	*S*	4	555.270*O*	*S*
5	616.309*O*	*S*	5	554.507*O*	*S*
3	610.80	*A*	3	554.066*O*	*S*
4	609.828*O*	*S*	3	553.318*O*	*S*
0	609.13	*A*			

$A=\pm 0.04$; $B=\pm 0.07$; $C=\pm 0.10$; S=Standard; $2S$=Two Standard Lines Averaged.

apart in the first order. The high dispersion and sharp focus obtainable with the use of a *concave* grating in this mounting is clearly indicated in the section on design and in the photographs. These photographs (except the 834 line) are 23.7 cm long on the original films.

Table I gives the measurements on the spectra using one electrode of magnesium and the other of carbon. The plates were measured on a Gaertner 8-cm comparator, and readings were corrected for errors in the screw. The lines of carbon, nitrogen, and oxygen (labeled S in Table I) given by I. S. Bowen and S. B. Ingram[1] and by Bowen[2] were used as standards. Wherever the lines could not be resolved sufficiently the mean (weighted for intensities) was used. Occasionally one of the lines was omitted from the calculations of the dispersion and its wave-length determined with the others. A comparison of the results so obtained is given in Table II. Separate graphs were made of the scale for each exposure, the scale values being plotted at the mean wave-length between the standards. Also in making the measurements the scale was chosen midway between the standard and the unknown line's roughly calculated wave-

[1] *Physical Review*, **28**, 444, 1926.

[2] *Ibid.*, **29**, 231, 1927.

length. This procedure was justifiable since the dispersion curves are very nearly straight lines (except near the ends of the plates). Each line was calculated from four to eight standard lines in its vicinity on each plate and averaged with similar sets from two to four exposures. The order of accuracy is given in the tables. Lines given only to the first decimal are probably correct to two- or three-tenths of an angstrom.

On No. 5, *a* and *c* show the spectrum taken under the usual conditions. In *b*, hydrogen was passed through the electrodes during the exposure, clearly bringing out the first line of the Lyman series

TABLE II

Standard	Measured
1561.381	1561.368*A*
1334.539	1334.490*A*
1085.650	1085.651*B*
1084.274	1084.355*B*
1025.732	1025.706*A*
977.031	977.063*A*
904.046	904.070*A*
787.716	787.744*A*
718.532	718.529*A*
687.202	687.256*B*
609.828	609.846*A*
608.390	608.340*B*
554.066	554.052*B*

at 1215 A. The second line at 1026 also appears on the original films.

On No. 6, *a* and *c* were taken in the usual way but hydrogen was passed into the source chamber during the *b*-exposure. A continuous spectrum is observed from 1085 to about 900 A.

On No. 7, *a* was taken in the usual way but nitrogen was passed through the magnesium electrode for *b*. The nitrogen lines at 1085, 1084−992, 990−917, and 916 are added.

The customary appearance of the 834 oxygen line is given in 8*a*. At certain times, however, it appears as in *b*. This occurs whenever a gas is passing through the electrodes and occasionally at other times. The lines 834.462 and 833.326 are brought out much stronger in *b* than in *a*, and 832.841 is somewhat enhanced. Bowen[1] gives

[1] *Ibid.*

these lines, and the shorter component of the 832.841 double, as due to o_{II} and the rest as due to o_{III}. This indicates that the degree of ionization is less marked when considerable gas exists between the electrodes (coming from the outside, or possibly from the heated electrodes). Further, when the 834 line has the appearance of 8*b*, very few of the o_{III}-lines appear in the spectrum, whereas most of them are present under the conditions of 8*a*.

In conclusion the author wishes to thank Dean H. G. Gale for suggesting the problem and for continued advice and encouragement during its development.

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August 15, 1927

SERIES AND IONIZATION POTENTIALS OF THE ELEMENTS OF THE IRON GROUP[1]

By HENRY NORRIS RUSSELL[2]

ABSTRACT

Identification of series and calculation of ionization potentials.—The recognition of the electronic configurations corresponding to the terms of complex spectra has made it possible to *identify series* (usually of two members only) in all the arc spectra from K to Zn and in the majority of the spark spectra from Ca^+ to Zn^+. A Rydberg formula, applied to the first two terms, gives *approximate series limits*. These have been corrected by an empirical formula, which, in the fifteen cases where the test can be made, gives results differing from those of the more exact Ritz formula by an average of ± 0.5 per cent. Values of the *first ionization potential* for all these elements, and of the *second* for all but V, Cr, Fe, and Co, have thus been obtained. Approximate values for the latter have been derived with the aid of Moseley's law.

For most of these elements, there are *four* important *modes of ionization* of the neutral atom, and *three* for the *second ionization*, corresponding to changes between various metastable states (and still others are possible). Tables of the values of these important ionization potentials are given.

The principal ionization potentials which measure the energy required for the change from the lowest energy state of the atom in one degree of ionization to the lowest energy state in the next are K, 4.32 volts; Ca, 6.09; Sc, 6.57; Ti, 6.80; V, 6.76; Cr, 6.74; Mn, 7.40; Fe, 7.83; Co, 7.81; Ni, 7.64; Cu, 7.69; Zn, 9.36; and for the *second* ionization, Ca^+, 11.82; Sc^+, 12.80; Ti^+, 13.60; V^+, (14.7); Cr^+, (16.6); Mn^+, 15.70; Fe^+, (16.5); Co^+, (17.2); Ni^+, 18.2; Cu^+, 20.34; Zn^+, 17.89.

These values should be accurate to 0.1 volt or better, except those in parentheses, which have been derived by Moseley's law, and may be in error by as much as 0.3 volt.

New terms in certain spectra.—New high terms, arising from configurations involving a 5s electron, have been identified in the spectra of V, Mn, Co, and Mn^+. *Tables* of these terms and of the multiplets involving them are given. The ionization potentials of V and Mn^+ have thus been determined for the first time.

I. INTRODUCTION

As appears from the data collected in the preceding communication,[3] series have now been detected in the arc spectra of all the elements of the iron group, and in the spark spectra of the majority. Most of the series consist of only two members, but even so they

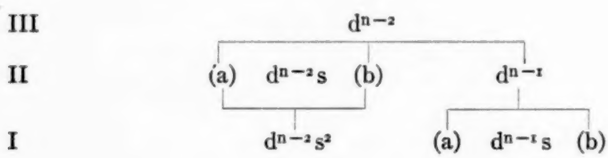
[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington,* No. 342.

[2] Research associate of the Mount Wilson Observatory, Carnegie Institution of Washington.

[3] *Mt. Wilson Contr.*, No. 341; *Astrophysical Journal*, **66**, 184, 1927.

should suffice to give fairly good values of the ionization potential. As a number of these series have been detected in the examination of the spectra made for the purpose of the preceding paper, it may be appropriate to give details concerning them and to collect the resulting values for the ionization potentials.

Most of the atoms of this group can exist in many metastable states, and there are usually a great many ionization potentials, corresponding to transitions from each metastable state of the neutral atom, for example, to those states of the ionized atoms which would be obtained by removing one electron. We shall consider here, however, only those which involve the normal state of the atom or ion, or the lowest metastable states. These may be represented schematically as follows:



For an atom with n electrons outside the "argon-shell" and atomic number $n+18$, the normal state, when doubly ionized, corresponds to the configuration d^{n-2}, in which all the electrons are in 3d orbits. Only the lowest of the numerous terms arising from this configuration concerns us here. By the addition of a 4s electron we obtain the configuration $d^{n-2}s$ in the singly ionized atom, from which the lowest terms are two of the same name as the "parent-terms," but of multiplicities greater and less by a unit, here denoted by (a) and (b). On account of Pauli's restriction, addition of a second 4s electron gives rise to but a single low term for the configuration $d^{n-2}s^2$. Addition of a 3d electron to the original configuration gives d^{n-1}, for which the lowest term is usually of a different name, and is of multiplicity higher by a unit, unless n exceeds 6, when it is lower by a unit. Adding a 4s electron to this gives two terms of the same name, $d^{n-1}s$ (a) and (b). Details of the resulting states for all the elements of the iron group with term values are given in Tables I and II of the preceding paper.

As an example, we may indicate the terms in *Mn:*

Mn III	$^6S(d^5)$	
Mn II	$^7S \quad (d^5 s) \quad ^5S$	$^5D(d^6)$
Mn I	$^6S(d^5 s^2)$	$^6D \quad (d^6 s) \quad ^4D$

There are usually four principal processes of ionization for the neutral atom, represented by the vertical lines in the diagram. (Two others which take the $d^{n-1}s$ terms into $d^{n-2}s$ by removal of a d electron need not be considered here). In each of the four processes the 4s electron is removed by stages, 5s, 6s, and gives rise to a series of terms with one of the principal spark terms as limit, and one of the principal arc terms as a first member. The second members of some of these series are known in all the spectra, and all four of them have been identified in *Mn* (see below) and in *Fe*, where they were detected by Laporte[1]—the first instance of the kind.

For the singly ionized atom there are three principal types of ionization: two involving the removal of an s electron from $d^{n-2}s$, and the other, a d electron from d^{n-1}. Second members of some of these series are known in all the spark spectra except those of *V*, *Cr*, *Fe*, and *Co*, and those of all three series in *Sc* II and *Ti* II. The series involving changes in a d electron, is, however, not Ritzian, so that calculations of the ionization potential must depend on the other two.

For atoms near the beginning and end of the group the number of possible states and series is smaller, as is shown in detail in the table already mentioned.

2. NEW TERMS IN *V*, *Mn*, *Co*, Mn^+

For most of the data on which the series here discussed are based, reference may be made to the sources mentioned in the preceding paper. Certain terms, however, which were found by the writer in the course of preparation of the tables, may be given here, with the resulting multiplets. The notation needs no comment, except to say that the term values are always measured from the lowest level in the spectrum. The suggested new term in *Ca* is a mere fragment, and the only reason for believing in its reality is that it falls in just

[1] *Proceedings of the National Academy of Sciences*, 12, 496, 1926.

TABLE I

New Multiplets in Arc Spectra

Ca I

		x^3D_3 46704.0			
a^3F_4....	35897.2	9250.8 (2) 10807.3 (06.8)	....	....	....
$a^3D'_3$....	38259.5	11840.0 (5) 8443.6 (44.5)	....	....	....

V I

		$b^4F'_5$ 39596.94	$b^4F'_4$ 39391.75	$b^4F'_3$ 39241.25	$b^4F'_2$ 39126.92
$a^4G'_6$....	22313.92	5784.42(5 III) 17283.03 (3.02)	....	....	....
$a^4G'_5$....	22121.09	....	5788.58(3 III) 17270.62 (0.66)	....	....
$a^4G'_4$....	21963.40	....	....	5786.21(7 III) 17277.69 (7.85)	....
$a^4G'_3$....	21841.40	....	....	....	5783.59(2 III) 17285.52 (5.52)
$b^4D'_4$....	21032.44	5385.13(3 III) 18564.50 (4.50)	....	....	....
$b^4D'_3$....	20828.49	....	.... (18563.26)	....	....
$b^4D'_2$....	20687.80	....	....	5388.30(1 III) 18553.58 (3.45)	....
$b^4D'_1$....	20606.46	....	....	....	5397.93(1 IV) 18520.48 (0.46)
b^4F_5....	23519.84	6218.31(3 IV) 16077.10 (7.10)	6298.68(tr IV A) 15871.96 (1.91)	....	....
b^4F_4....	23353.06	....	6233.20 (12 I A)* 16038.95 (8.69)	....	....
b^4F_3....	23210.52	....	....	6236.28(1 IV) 16030.75 (0.73)	....
b^4F_2....	23088.04	....	....	....	6233.20(12 I A)* 16038.95 8.88

* Masks the expected line.

TABLE I—*Continued*

Mn I

		c^6D_5 56189.46	c^6D_4 56356.11	c^6D_3 56490.49	c^6D_2 56616.57
$a^6D'_5$....	41789.44	6942.57(5) 14399.92 (0.02)	6863.08(2) 14566.70 (6.67)	....	....
$a^6D'_4$....	41932.64	7012.22(2) 14256.88 (6.82)	6931.27(3) 14423.40 (3.47)	6867.18(2) 14558.00 (7.85)	....
$a^6D'_3$....	42053.70	....	6989.85(4) 14302.52 (2.41)	....	....
a^6F_6....	43314.23	7764.75(5) 12875.05 (5.23)	....	....	....
a^6F_5....	43428.56	7834.32(2) 12760.85 (0.90)	7733.23(4n) 12927.64 (7.55)	....	....
a^6F_4....	43524.09	....	7790.91(2) 12831.96 (2.02)	7710.21(5) 12966.23 (6.40)	....
a^6F_3....	43595.47	....	....	7752.78(3) 12895.05 (5.02)	7677.80(1) 13020.98 (1.10)
a^6F_2....	43644.46	....	....	....	7706.64(2) 12972.27 (2.11)
c^6P_4....	44993.89	8929.66(1) 11195.56 (5.57)	....	....	....

Co I†

		$c^4F'_5$ 44782.00	$c^4F'_4$ 45105.44	$c^4F'_3$ 45876.44	$c^4F'_2$ 46375.00
$a^4D'_4$....	29294.49	6455.03(10 III) 15487.53 (7.51)	6322.94(2) 15811.06 (0.95)	....	....
$a^4D'_3$....	29948.74	....	6595.91(9 V) 15156.73 (6.70)	6276.62(5)‡ 15927.75 (7.70)	....
$a^4D'_2$....	30443.56	....	....	6477.93(9 V) 15432.77 (2.88)	6275.16(4) 15931.45 (1.44)
$a^4D'_1$....	30742.55	....	....	....	6395.19(7 V) 15632.44 (2.45)

† The intensities are those tabulated by Meggers; King's temperature classification is added when available.

‡ Blend.

TABLE I—*Continued*

		$c^4F'_5$ 44782.00	$c^4F'_4$ 45105.44	$c^4F'_3$ 45876.44	$c^4F'_2$ 46375.00
Co I—*Continued*					
a^4F_5....	28345.80	6082.49(10 III) 16436.10 (6.20)	5965.02(3) 16759.77 (9.64)	....	....
a^4F_4....	28777.19	6246.42(2) 16004.75 (4.81)	6122.68(10 IV?) 16328.20 (8.25)	5846.57(3 V) 17099.31 (9.25)	....
a^4F_3....	29216.32	....	6291.89(3) 15889.09 (9.12)	6000.70(8 I) 16660.11 (0.12)	5826.30(4) 17158.81 (8.68)
a^4F_2....	29563.05	....	....	6128.26(3) 16313.34 (3.39)	5946.51(7 III) 16811.94 (1.95)
$a^4G'_6$....	28845.16	6273.06(7 III?)§ 15936.79 (6.84)	....	....	....
$a^4G'_5$....	29269.68	6444.75(6 V)‖ 15512.22 (2.32)	6313.07(6) 15835.79 (5.76)	....	....
$a^4G'_4$....	29735.09	6643.78(3) 15047.62 (6.91)	6504.25(4) 15370.32 (0.35)	6193.58(6) 16141.29 (1.35)	....
$a^4G'_3$....	30102.88	....	6663.68(2) 15002.59 (2.56)	6337.98(3) 15773.54 (3.56)	6143.78(4) 16272.13 (2.12)
$b^4D'_4$....	32027.42	7838.18(8 V) 12754.57 (4.58)	....	....	....
$b^4D'_3$....	32654.45	....	8029.29(7) 12450.98 (0.99)	7561.08(4) 13221.99 (1.99)	....
$b^4D'_2$....	33150.60	....	....	7855.88(7) 12725.82 (5.84)	7559.68(3) 13224.44 (4.40)
$b^4D'_1$....	33449.04	....	....	....	7734.25(6) 12925.95 (5.96)
b^4F_5....	32841.91	8372.82(10) 11940.14 (0.09)	8152.03(6) 12263.52 (3.53)	....	....
b^4F_4....	33466.78	8835.22(8) 11315.23 (5.22)	8589.70(3) 11638.66 (8.66)	8056.03(8 V) 12409.65 (9.66)	....
b^4F_3....	33945.81	....	8958.46(6) 11159.57 (9.63)	8379.54(3) 11930.56 (0.63)	8043.33(8 V) 12429.25 (9.19)
b^4F_2....	34196.11	....	....	8559.04(2) 11680.36 (0.33)	8208.67(8) 12178.91 (8.89)

§ Blend.

‖ Masks the expected line.

TABLE I—*Continued*

Co I—*Continued*

		$c^4F'_5$ 44782.00	$c^4F'_4$ 45105.44	$c^4F'_3$ 45876.44	$c^4F'_2$ 46375.00
$b^4G'_6$....	32430.56	8094.03(10 III) 12351.39 (1.44)	....	....	....
$b^4G'_5$....	32464.66	8116.43(7) 12317.31 (7.34)	7908.75(10 III?) 12640.25 (0.78)	....	....
$b^4G'_4$....	33173.30	....	8378.37(7) 11932.23 (2.14)	7869.92(6 V) 12703.12 (3.14)	....
$b^4G'_3$....	33674.32	....	....	8193.05(8) 12202.12 (2.12)	7871.43(6 V) 12700.68 (0.68)
$a^2D'_3$....	33462.80	....	8586.71(3) 11642.72 (2.64)	8053.50(1) 12413.55 (3.64)	....
$a^2D'_2$....	34352.38	....	....	8675.02(1) 11524.19 (4.06)	8315.32(2) 12022.70 (2.62)
a^2F_4....	31871.09	7743.27(5) 12910.89 (0.91)	7554.04(8 IV) 13234.31 (4.35)	....	....
a^2F_3....	32781.64	....	8112.13(1) 12323.84 (3.80)	7634.56(5) 13094.73 (4.80)	....
$a^2G'_5$....	31699.61	....	7457.43(8 V) 13405.77 (5.83)	....	....
$a^2G'_4$....	32732.99	8296.85(5) 12049.47 (9.01)	8080.23(5) 12372.49 (2.45)	7606.30(2 V)§ 13143.39 (3.45)	....
$b^2G'_5$....	33439.64	....	8569.72(2) 11665.79 (5.80)	....	....
$b^2G'_4$....	34133.50	....	....	8513.48(1) 11742.86 (2.94)	....

§ Blend.

TABLE I—*Continued*

Co I—*Continued*

		$b^2F'_4$ 45924.82	$b^2F'_3$ 46745.83
$a^2D'_3$..	....	8022.15(7) 12462.07 (2.02)	7526.32(1) 13283.06 (3.03)
$a^2D'_2$..	....	....	8066.50(7) 12293.55 (3.45)
a^2F_4..	....	7113.74(9 V) 14053.43 (3.73)	6720.97(2) 14874.71 (4.74)
a^2F_3..	....	7606.30(2 V)§ 13143.39 (3.18)	7159.23(8 V) 13964.14 (4.19)
$a^2G'_5$..	....	7027.86(8 V) 14225.17 (5.21)	....
$a^2G'_4$..	....	7578.34(1) 13191.88 (1.83)	7134.37(8 V) 14012.81 (2.84)
b^2F_4..	35450.51	9544.52(2) 10474.35 (4.31)	8850.74(10) 11295.39 (5.32)
b^2F_3..	36329.79	(9595.03)	9597.89(2) 10416.10 (6.04)
$b^2G'_5$..	....	8007.34(10 V) 12485.11 (5.18)	....
$b^2G'_4$..	....	8478.45(2) 11791.38 (1.32)	7926.59(8 V) 12612.30 (2.33)
$a^4D'_4$..	....	6011.43(3) 16630.38 (0.33)	....
$a^4D'_3$..	....	6257.56(10 III) 15976.28 (6.08)	5951.73(2) 16797.20 (7.09)
$a^4D'_2$..	....	....	6132.44(3) 16302.22 (2.27)
a^4F_5..	....	5686.96(3) 17579.22 (9.02)	....
a^4F_4..	....	5830.05(7 V) 17147.77 (7.63)	....
a^4F_3..	....	5983.36(3) 16708.39 (8.50)	5703.03(2) 17529.69 (9.51)
a^4F_2..	....	....	5818.09(2) 17183.02 (2.78)

		$b^2F'_4$ 45924.82	$b^2F'_3$ 46745.83
$a^4G'_5$..	....	6002.48(3) 16655.18 (5.14)	....
$a^4G'_4$..	....	6175.08(2) 16189.65 (9.73)	....
$a^4G'_3$..	....	6318.55(4u) 15822.05 (1.94)	....
$b^4D'_4$..	....	7193.63(8 V) 13897.37 (7.40)	....
$b^4D'_3$..	....	7533.52(5 IV) 13270.35 (0.37)	7094.64(4 IV) 14091.27 (1.38)
$b^4D'_2$..	....	....	7353.48(2) 13595.26 (5.23)
b^4F_5..	....	7641.43(1) 13082.97 (2.91)	....
b^4F_4..	....	8024.75(4) 12458.03 (8.04)	....
b^4F_3..	....	8345.59(2) 11979.10 (9.01)	7810.39(1) 12799.95 (0.02)
b^4F_2..	....	....	7966.12(2) 12549.72 (9.72)
$b^4G'_4$..	....	7840.05(7) 12751.52 (1.52)	....
$b^4G'_3$..	....	8160.68(2) 12250.52 (0.50)	7648.19(4) 13071.39 (1.51)

§ Blend.

the right position, the limit of the series being known from other data. Further observations in the infra-red are desirable to confirm or disprove it.

The new multiplets in *V* are weak, in *Mn* fairly strong, though the intensities fall off so rapidly that the component of lowest inner-quantum number cannot be identified. Those in *Co* are remarkably strong, and account for almost all the heavy lines in the deep red. In all these cases the position of the high term was approximately predicted by means of the regularities discussed in the preceding paper, and the multiplets were then very easily found.

The resulting series in *V* I converge to the $^3F'$ term of the spark spectrum, thus giving the ionization potential which was previously unknown. Those in *Co* I also converge to a $^3F'$ term, which must be the lowest in the spark spectrum, which is very incompletely analyzed. The series in *Mn* I converges to the ^5D term in *Mn* II, as does also one involving a ^4D term, previously known. This gives a good approximation to the relative levels of the ^7S and ^5D terms in *Mn* II, and made it rather easy to find the intersystem combinations which fix these levels exactly.[1] Further search revealed an "inverted" triplet which locates a high ^7S term in series with the low one. These lines are given by Exner and Haschek, but have been remeasured on a plate kindly taken by Mr. King. They appear in the spark only, and are unsymmetrical and diffuse toward the red, differing widely in this respect from any other lines in the neighborhood—all of which characteristics are just what might be expected of lines arising from the transition to which they have been attributed. The frequency differences are also in very good agreement.

All of the lines of *Mn* II which thus far have been classified are given in Table II. This spectrum includes many other strong lines which probably arise from metastable terms not yet identified. The triplet of the quintet system, corresponding to that found in the septets, was sought for in vain and is probably faint.

3. THE SERIES LIMITS

By applying a simple Rydberg formula to the first two terms of any series, an approximate value of the limit and the ionization

[1] These combinations have been found independently by Black and Duffendack. *Science*, **66**, 402, 1927.

TABLE II

Mn II*

		SEPTETS					QUINTETS				
		a^7P_4 38806.52	263.58	a^7P_3 38542.94	176.91	a^7P_2 38366.03	a^5P_3 43370.40	114.08	a^5P_2 43484.48	72.45	a^5P_1 43556.93
a^7S_3	0.00	2576.12(30R) 38806.52 (6.52)		2593.73(15R) 38542.94 (2.94)		2605.70(10R) 38366.03 (6.03)	2305.02(2) 43370.2 (0.4)		2298.97(2) 43484.4 (4.5)		
a^5S_2	9472.86			3438.99(3 V) 29070.00 (0.08)		3460.04(2) 28893.16 (3.17)	2949.21(30 IV) 33897.54 (7.54)		2939.32(20 V) 34011.62 (1.62)		2933.06(15 V) 34084.07 (4.07)
a^5D_4	14324.47 *269.29*						3442.00(30 V) 29045.93 (5.93)				
a^5D_3	14593.76 *187.32*						3474.05(15 V) 28776.65 (6.64)		3460.33(20 V) 28890.71 (0.72)		
a^5D_2	14781.08 *120.00*						3496.82(3 V) 28589.30 (9.32)		3482.92(12 V) 28703.37 (3.40)		3474.14(15 V) 28775.90 (5.85)
a^5D_1	14901.08 *58.59*								3497.54(6 V) 28583.37 (3.40)		3488.62(10 V) 28655.89 (5.85)
a^5D_0	14959.67										3495.84(7 V) 28597.26 (7.26)

* Intensities from Exner and Haschek (spark); temperature classes from King.

TABLE II—*Continued*

		Septets			Quintets		
		a^7P_4 38806.52 *263.58*	a^7P_3 38542.94 *176.91*	a^7P_2 38366.03	a^5P_3 43370.40 *114.08*	a^5P_2 43484.48 *72.45*	a^5P_1 43556.93
a^7D_5.....	79568.4 *10.2*	2452.63(10) 40761.9 (1.9)	...	...	...	...	...
a^7D_4.....	79558.2 *9.0*	2453.17(2) 40751.3 (1.7)	2437.45(5) 41015.7 (5.3)	...	2762.57(1) 36187.5 (7.8)	...	...
a^7D_3.....	79549.2 *5.4*	2453.65(1) 40743.0 (2.7)	2437.92(3) 41006.1 (6.3)	2427.43(3) 41183.3 (3.2)	2763.19(1) 36179.5 (8.8)	...	...
a^7D_2.....	79543.8 *3.7*	...	2438.22(3) 41001.1 (0.9)	2427.77(4) 41177.5 (7.8)	...	...	...
a^7D_1.....	79540.1	...	...	2427.97(4) 41174.1 (4.1)	...	...	...
b^7S_3.....	74558.69	2796.21(3 h r) 35752.13 (2.17)	2775.75(2 h r) 36015.70 (5.75)	2762.17(1 h r) 36192.75 (2.66)	...	...	...

potential can be obtained. Experience shows that this value is usually nearly correct when the series is produced by the removal of an s electron, since in such series the Ritz correction is almost always small. Series involving changes in a d electron are usually very regular, except for the lowest term, when this involves the binding of the electron as part of an incomplete shell. In this case the energy of binding is considerably increased, and the application of a simple Rydberg formula puts the limit a great deal too high.

Series involving a p electron, when d orbits are also present in the atom, are usually quite incapable of representation by a simple formula,[1] and the application of one to the first two terms would give wholly wild results.

In the iron group the majority of the series which can be identified are fortunately of the most favorable type for discussion with limited data. By applying the Rydberg formula to the data given in Tables I and II of the previous paper the results listed in Table III were obtained. For brevity the four types of series which may in general appear in the spectrum are here denoted as follows:

A	$d^{n-2}s^2$	to limit $d^{n-2}s$	(a)	(higher multiplicity)
B	$d^{n-2}s^2$	to limit $d^{n-2}s$	(b)	(lower multiplicity)
C	$d^{n-1}s$ (a)	to limit d^{n-1}		
D	$d^{n-1}s$ (b)	to limit d^{n-1}		

The series C and D should have the same limit, but the limits of A and B differ from this and from each other. When the differences between these limits (which are well-known terms of the spark spectrum) are found from analysis of that spectrum, a direct check upon the relative accuracy of the approximation involved in using the Rydberg formula is possible. Its absolute accuracy can be tested only when at least one series is known in which there are three or more terms, and when a Ritz formula can be employed. The other limits may then be found from that of this series by adding the differences of level which have been determined in the spark spectrum.

The first column of Table III gives the element and the second the designation of the series, as just explained. The third and fourth

[1] Cf. Fowler, *Report on Line Spectra* (London, 1922), p. 42.

columns give the term values, from Table I of the preceding paper, for the configurations including a 4s and a 5s electron, and the next the limit (which is the energy level of the corresponding state of the spark spectrum referred to the standard energy level in the arc spectrum) as derived by a Rydberg formula. The sixth column gives the relative levels of these limits as determined from the analysis of the spark spectrum, and the next, the absolute levels determined by a Ritz formula when three or more members of some series are known.

The third member of the A series in *Fe* I suggested by Gieseler and Grotrian[1] has not been included. It is determined by a single multiplet of faint lines, a combination from the ^5P term. Most of the energy levels involved are clearly real, but they do not combine with the related $^5D'$ or ^5F terms, and it is therefore very improbable that they represent the $d^{n-2}s$ (6s) configuration. The term separations are also much smaller than those of the other two series members, or the limiting F term a^6D in *Fe* II. The doubts regarding this term expressed by Laporte[2] appear to be fully justified.

In the spark spectra we have two types of series:

C $d^{n-1}s$ (a) to limit d^{n-1}
D $d^{n-1}s$ (b) to limit d^{n-1}

The corresponding table (Table IV) is simple, since there is but a single limit.

The series in Tables III and IV refer in all cases to the leading component (of greatest inner-quantum number), and the limits give the leading components of the spark terms. The subtraction of the quantities given in Table III under the heading "Spark" suffices to reduce these to determinations of the relative position of the levels used as origins of measurement in the two cases. A similar correction cannot yet be made for the spark spectra, as the multiplet separations of the lowest terms in the third spectra are known only for *Sc* III and *Ti* III. This correction is, however, too small to be of practical importance.

The next to the last column of Tables III and IV gives the error in the limit determined from the first two members by a Rydberg

[1] *Zeitschrift für Physik*, **25**, 169, 1924.

[2] *Proceedings of the National Academy of Sciences*, **12**, 502, 1926.

formula, expressed as a percentage of the distance from the lowest term to the limit. It is positive, i.e., the first two members indicate

TABLE III

SERIES LIMITS IN THE ARC SPECTRA OF THE IRON GROUP

Element	Type	4s	5s	Rydberg	Spark	Ritz	Percentage Error	Comp. Error
K......	C	0	21,026	35,439	0	35,006	+1.2	+1.6
Ca.....	A	0	33,317	51,438	0	49,305	+4.3	2.3
	C	20,371	46,704	62,841	13,711	63,016	−0.7	1.9
Sc.....	A	168	35,746	54,453	178	....	......	2.4
	C	11,677	42,085	59,414	4988	....	......	2.2
Ti.....	A	387	37,825	56,995	393	55,523	+2.7	2.6
	B	387	39,786	59,429	4898	60,028	−1.0	2.7
	C	6843	39,413	57,334	1216	56,346	+2.0	2.3
V......	A	553	39,597	59,154	558	....	......	2.7
Cr.....	A	557	41,074	60,980	0	59,388	2.6	2.7
	C	− 7751	29,145	48,182	−12,498	46,890	2.8	2.5
	D	− 158	30,132	47,428	−12,498	46,890	1.1	2.2
Mn....	A	0	41,404	61,515	0	59,937	2.6	2.7
	B	0	49,415	71,262	9473	69,410	2.7	3.2
	C	17,052	56,190	75,770	14,324	74,261	2.6	2.7
	D	23,297	57,306	75,607	14,324	74,261	2.6	2.4
Fe.....	A	0	44,677	65,523	0	....	......	2.9
	B	0	51,351	73,587	7955	....	......	3.3
	C	6928	47,006	66,808	1873	....	......	2.7
	D	11,976	47,961	66,743	1873	....	......	2.5
Co.....	A	0	47,524	68,979	0	....	......	3.1
	C	3483	44,782	64,371	−?	....	......	2.7
	D	7442	45,925	65,349	−?	....	......	2.6
Ni.....	A	0	50,466	72,526	0	....	......	3.3
	C	205	42,606	62,944	−?	....	......	2.8
	D	3410	44,263	64,247	−?	....	......	2.7
Cu.....	A	0	53,455	74,911	0	73,030	2.6	3.4
	C	−11,202	31,934	52,438	−21,925	51,105	2.2	2.8
Zn.....	A	0	55,788	78,883	0	75,767	+4.1	+3.6

too high a limit, for all the series but two, which happen to be about the least reliable of the lot. The rejected term in *Fe* also led to a negative error.

For the rest of the series the percentage error is clearly a function

of the length of the series itself. Dividing the terms for the spark spectrum by 4 to make them comparable with the others, and taking means by groups, we find:

Length of series......	32,300	50,500	59,000	75,000
Percentage error......	+1.5	+2.5	+2.6	+3.1
Number.............	3	4	6	3

These may be represented by the empirical formula

$$\text{Percentage error} = 4.5 \times 10^{-5} \times (\text{length of series}).$$

TABLE IV

SERIES LIMITS IN THE SPARK SPECTRA OF THE IRON GROUP

Element	Type	4s	5s	Rydberg	Ritz	Percentage Error	Comp. Error
Ca^+......	C	0	52,167	97,060	95,748	+1.4	+1.1
Sc^+......	C	178	57,743	105,046	....	....	1.2
	D	2541	58,252	104,745	....	....	1.2
Ti^+......	C	393	62,594	111,874	....	....	1.3
	D	4898	63,445	111,174	....	....	1.2
Mn^+......	C	0	74,558	128,715	....	....	1.5
Ni^+......	C	0	83,404	140,772	....	....	1.6
	D	5156	85,132	141,284	....	....	1.6
Cu^+......	C	0	86,084	144,388	....	....	1.6
	D	4336	88,435	146,048	....	....	1.6
Zn^+......	C	0	88,436	147,548	144,890	+1.8	+1.6

The values computed by this formula are given in the last column of the tables. The average difference between the observed and computed errors is ±0.5 per cent (rejecting the two anomalous series already mentioned). It appears probable, therefore, that the application of these computed corrections, in the cases where only the Rydberg formula can be employed, will lead to rather accurate values for the limits. The resulting values are collected in Table V, which gives the distance of the lowest term of each of the series A, B, C, and D from its own proper limit, rounded off by omission of the last two figures, which in this case are quite uncertain.

The values have been adjusted to take account of the known

TABLE V

LIMITS FROM EMPIRICALLY CORRECTED RYDBERG FORMULAE

Series	Element	ν	Element	ν	$\sqrt{\nu/R}$		
					Arc	Spark	Diff.
C......	*K*	34,800	Ca^+	96,000	0.619	0.936	0.317
A......	*Ca*	50,300	Sc^+	....	....	....	....
C......	*Ca*	43,700	Sc^+	103,700	.632	.973	.341
D......	*Ca*	42,200	Sc^+	101,200	.622	0.961	.339
A......	*Sc*	53,200	Ti^+	....	....	....	....
B......	*Sc*	55,700	Ti^+	....	....	....	....
C......	*Sc*	46,500	Ti^+	110,200	.652	1.003	.351
D......	*Sc*	43,200	Ti^+	105,300	.628	0.980	.352
A......	*Ti*	55,000	V^+	....	....	....	....
B......	*Ti*	59,900	V^+	....	....	....	....
C......	*Ti*	49,400	V^+	(116,000)	.672	(1.030)	(.358)
D......	*Ti*	44,400	V^+	(109,000)	.637	(0.999)	(.362)
A......	*V*	57,000	Cr^+	....	....	....	....
B......	*V*	63,500	Cr^+	....	....	....	....
C......	*V*	52,300	Cr^+	(122,000)	.692	(1.056)	(.364)
D......	*V*	46,000	Cr^+	(114,000)	.649	(1.020)	(.371)
A......	*Cr*	59,000	Mn^+	....	....	....	....
B......	*Cr*	66,500	Mn^+	....	....	....	....
C......	*Cr*	54,300	Mn^+	126,800	.705	1.076	.371
D......	*Cr*	46,700	Mn^+	117,300	.654	1.035	.381
A......	*Mn*	59,800	Fe^+	....	....	....	....
B......	*Mn*	69,300	Fe^+	....	....	....	....
C......	*Mn*	57,200	Fe^+	(133,000)	.723	(1.100)	(.377)
D......	*Mn*	50,900	Fe^+	(124,000)	.682	(1.066)	(.384)
A......	*Fe*	63,400	Co^+	....	....	....	....
B......	*Fe*	71,400	Co^+	....	....	....	....
C......	*Fe*	58,300	Co^+	(136,000)	.730	(1.112)	(.382)
D......	*Fe*	53,300	Co^+	(129,000)	.698	(1.084)	(.386)
A......	*Co*	66,800	Ni^+	....	....	....	....
B......	*Co*	?	Ni^+	....	....	....	....
C......	*Co*	59,800	Ni^+	138,800	.739	1.126	.387
D......	*Co*	55,900	Ni^+	133,600	.714	1.103	.389
A......	*Ni*	70,100	Cu^+	....	....	....	....
B......	*Ni*	....	Cu^+	....	....	....	....
C......	*Ni*	61,700	Cu^+	142,800	.750	1.141	.391
D......	*Ni*	58,510	Cu^+	138,500	.732	1.124	.392
A......	*Cu*	72,500	Zn^+	....	....	....	....
B......	*Cu*	76,800	Zn^+	....	....	....	....
C......	*Cu*	61,900	Zn^+	145,200	0.751	1.150	0.399
A......	*Zn*	76,100	Ga^+	....	....	....	....

differences in level of the arc and spark terms. For example, for *Fe* I, subtracting from the values in the fifth column of Table III, which give the levels of the limits compared with the standard level in the arc as determined by the Rydberg formula, the corrections obtained by multiplying the distance of each term from its limit by the percentages given in the last column, we find for A, B, C, and D, to the nearest hundred, 63,600, 71,200, 65,200, 65,400. Subtracting from these again the spark levels given in the sixth column, we find 63,600, 63,200, 63,300, 63,500, which are four independent determinations of the difference between the lowest levels in the arc and

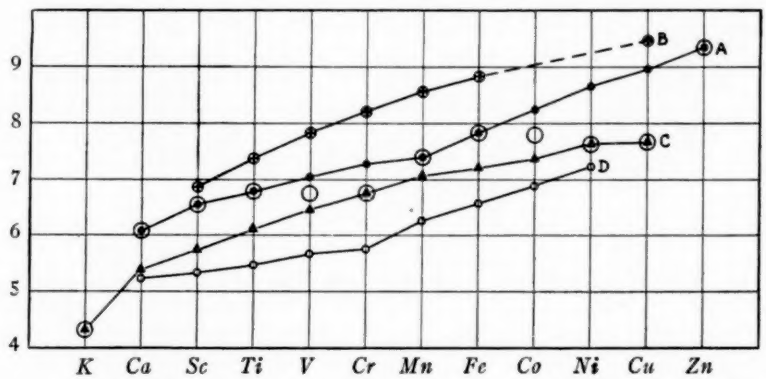


FIG. 1.—Ionization potentials of arc spectra. Large circles denote principal ionization potential.

spark. The mean, 63,400, is entered in Table V under "A" (where it belongs). The differences B, C, and D are then found by adding the level differences in the spark for their respective limits, and subtracting those in the arc. A considerable number of entries can thus be obtained for series in which only the first term and the limit are known.

The resulting limit-values, which represent the energy of homologous ionization processes in the successive spectra, run very smoothly, increasing steadily with the atomic number, so much so that it would probably be fairly accurate to fill in the missing values for the spark spectra by simple interpolation. It may be preferable, however, to apply Moseley's law. According to this, the differences of the quantities $\sqrt{\nu/R}$, where R is the Rydberg constant and ν the

quantity which is given in Table V (i.e., the term value referred to its own limit), should be nearly constant for successive corresponding spectra. The values are given in the latter part of Table V, and run very smoothly, so far as known. When plotted, they show a break in the slope of the curve at the point of maximum multiplicity, *Cr* I and *Mn* II, such as is exhibited in several other cases in Figures 1, 2, and 3 of the preceding paper and Figure 1 here. Interpolating the values of this difference numerically across the gaps and calculating backward to the term values in those spark spectra for which they are

TABLE VI

IONIZATION POTENTIALS

Element	Neutral Atom					Ionized Atom			
	A	B	C	D	Principal	C	D	E	Principal
K......	....	....	4.30	....	**4.32**	....	....	....	....
Ca.....	6.21	....	5.39	5.22	**6.09**	11.83	....	10.13	**11.82**
Sc......	6.57	6.88	5.74	5.33	6.57	12.80	12.49	12.19	12.80
Ti......	6.79	7.39	6.10	5.48	**6.80**	13.60	12.99	13.45	13.60
V......	7.04	7.84	6.46	5.68	6.76	14.4	13.5	14.7	14.7
Cr......	7.28	8.21	6.70	5.76	**6.74**	15.1	14.1	16.6	16.6
Mn.....	7.38	8.55	7.06	6.28	**7.40**	15.70	14.52	13.80	15.70
Fe......	7.83	8.81	7.20	6.58	7.83	16.5	15.4	16.3	16.5
Co......	8.25	9.0	7.38	6.90	7.81	16.8	16.0	17.2	17.2
Ni......	8.65	9.30	7.62	7.22	7.64	17.15	16.50	18.2	18.2
Cu.....	8.95	9.48	7.63	....	**7.69**	17.62	17.09	20.34	20.34
Zn.....	9.40	....	....	....	**9.36**	17.93	....	....	**17.89**

unknown, we find the values given in parentheses in Table V. From the general run of the other curves, it seems probable that the error in the estimated differences of $\sqrt{\nu/R}$ does not much exceed 0.01, which would correspond to about 2300 wave-numbers in the estimated term values in the spark.

From the data of Table V the various ionization potentials of the atoms can immediately be derived. These are collected in Table VI. For convenience the notation is repeated. The ionization denoted by

A is $d^{n-2}\ s^2$ to $d^{n-2}\ s$ (greater multiplicity)
B is $d^{n-2}\ s^2$ to $d^{n-2}\ s$ (smaller multiplicity)

$$\text{C is}\begin{cases} d^{n-1}\ s \text{ (greater mult.) to } d^{n-1} \text{ (arc)} \\ d^{n-2}\ s \text{ (greater mult.) to } d^{n-2} \text{ (spark)} \end{cases}$$

$$\text{D is}\begin{cases} d^{n-1}\ s \text{ (smaller mult.) to } d^{n-1} \text{ (arc)} \\ d^{n-2}\ s \text{ (smaller mult.) to } d^{n-2} \text{ (spark)} \end{cases}$$

E is d^{n-1} to d^{n-2} (spark)

The values listed under these headings are all derived from the first two members of the series by means of a Rydberg formula corrected as described above.

The "principal" ionization potentials represent the difference in energy between the normal states of the atoms in successive degrees of ionization. Those for *Ca, Sc, Ti, Mn, Fe,* and *Zn* correspond to a

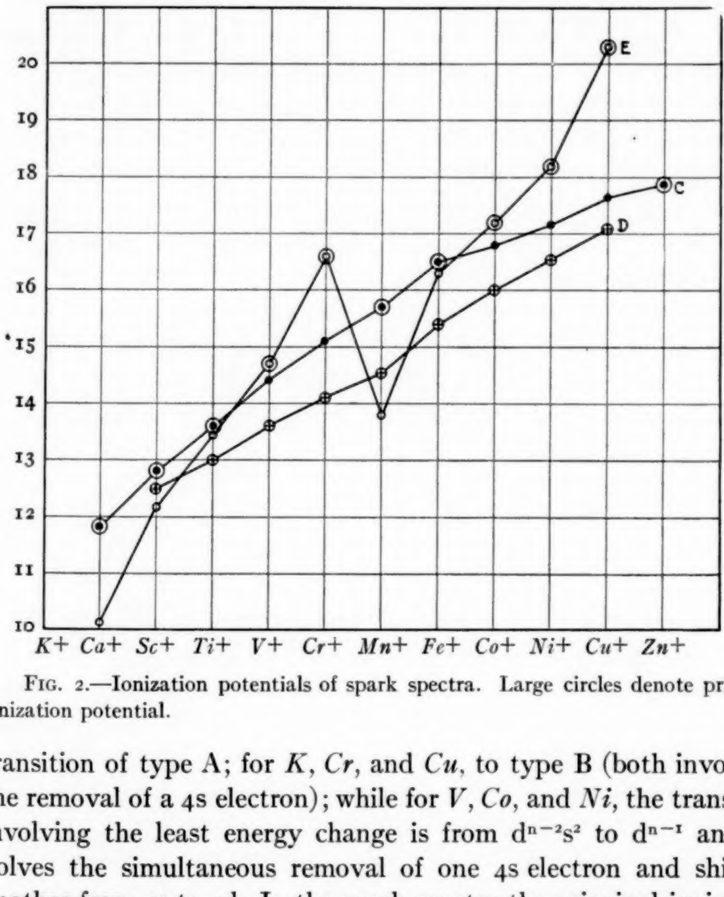


FIG. 2.—Ionization potentials of spark spectra. Large circles denote principal ionization potential.

transition of type A; for *K, Cr,* and *Cu,* to type B (both involving the removal of a 4s electron); while for *V, Co,* and *Ni,* the transition involving the least energy change is from $d^{n-2}s^2$ to d^{n-1} and involves the simultaneous removal of one 4s electron and shift of another from 4s to 3d. In the spark spectra the principal ionization involves the removal of an s electron in *Ca, Sc, Ti, Mn, Fe,* and *Zn,* and of a d electron in *V, Cr, Co, Ni,* and *Cu.* The values given in heavy type are derived from longer series and are of course to be preferred. The average difference between these and the values

given by the approximate formula is ± 0.04 volt and the greatest, 0.12 volt for *Ca*, so that the approximation appears to be a good one.

For V^+, Cr^+, Fe^+, and Co^+, the ionization potentials have been derived from those of the neutral atoms: *Ti*, *V*, *Mn*, *Fe*, by the application of Moseley's law. These values are given to only one decimal place, and may be wrong by two- or three-tenths of a volt, but probably not more.

The ionization potentials are plotted in Figures 1 and 2. The smooth course of the values corresponding to the removal of a 4s electron under similar conditions contrasts strikingly with the ragged sequence of those for a 3d electron (Fig. 2). The principal ionization potentials are marked with large circles. The way in which the irregularity of their run arises from alternations between processes C and E in the spark spectra, or C and A in the arc, is now immediately comprehensible.

Much work remains to be done on many of these spectra, but the present summary may be of use, both in astrophysical and physical applications, and in suggesting profitable lines for fresh spectroscopic analysis.

Carnegie Institution of Washington
Mount Wilson Observatory
June 16, 1927

ADDENDUM

The differences between the ionization potentials A and B, or C and D, admit of a simple explanation. The reverse process for the transitions C and D, whether in the arc or the spark, consists of adding a 4s electron to a partially completed shell of 3d electrons. In case C, the multiplicity is increased; that is, the added electron is spinning in the same direction as the resultant spin of those already present. In case D, it is spinning in the opposite direction. Now, as Hund has pointed out, the magnetic interaction produces attraction in the first case, and repulsion in the second, so that the energy of binding is greater for C than for D.

The magnetic moment M of the group of d electrons increases from a single magneton in *Ca* and Sc^+ to five in *Cr* and Mn^+ and then diminishes to one unit in *Ni* and Cu^+. The differences C – D are

actually nearly proportional to M, and greater in the spark than the arc spectrum. The differences $A-B$ in the arc spectrum are necessarily identical with $C-D$ in the spark.

The curious discontinuity in the run of the ionization potentials E is now intelligible. The reverse of this transaction involves the addition of a 3d electron to a group of similar electrons. From Ca^+ to Cr^+, the multiplicity is increased by the change; beyond this, owing to Pauli's restriction, it is diminished. The magnetic force should therefore change sign between Cr^+ and Mn^+, just where the observed discontinuity occurs. In the arc spectra the difference in energy between the configurations $d^{n-2}s^2$ and $d^{n-1}s$ should show a similar discontinuity between the same elements; and so it does.

The means of the values A and B, or C and D, should be uninfluenced by this effect of spin. They actually run much more smoothly than either series alone, increasing by almost uniform increments. This makes it possible to represent the ionization potentials approximately by means of very simple empirical equations as follows, Z being the atomic number, and M the magnetic moment defined above.

Arc Spectrum	Spark Spectrum
$A=0.320Z-0.13M$	$C=0.601Z+0.13M$
$B=.320Z+.13M$	$D=0.601Z-.13M$
$C=.262Z+.10M$	$E=1.12Z\pm0.40M-12.00$
$D=0.262Z-0.10M$	

The values resulting from these formulae, and the residuals for the observational data, are as shown on page 254. (Residuals depending on terms not observed, but estimated as series limits, are given in parentheses.)

For the six types of ionization corresponding to the removal of a 4s electron, the agreement is remarkably good (except for K I, which is quite out of line with the others). The mean, regardless of sign, of the fifty residuals (rejecting K I and the less accurate values in parentheses) is ±0.066 volt. Only five disposable constants appear in the formulae which represent these fifty observed values so closely. It is evident, therefore, that the processes of ionization of the elements of the iron group are remarkably regular. The nine

	Neutral Atom								Ionized Atom					
	A	O—C	B	O—C	C	O—C	D	O—C	C	O—C	D	O—C	E	O—C
K......	......	......	......	......	5.02	−0.72								
Ca......	6.40	−0.19	......	......	5.38	+0.01	5.18	+0.04	12.02	−0.19	......	......	10.40	−0.27
Sc......	6.59	− .02	6.85	+0.03	5.74	.00	5.34	− .01	12.75	+ .05	12.49	0.00	11.92	+ .27
Ti......	6.78	+ .01	7.30	+ .09	6.11	− .01	5.51	− .03	13.48	+ .12	12.96	+ .03	13.44	+ .01
V......	6.97	+ .07	7.75	+ .09	6.47	− .01	5.67	+ .01	14.21	(+ .2)	13.43	(+ .1)	14.96	(− .3)
Cr......	7.16	+ .12	8.20	+ .01	6.83	− .13	5.83	− .07	14.94	(+ .2)	13.90	(+ .2)	16.48	(+ .1)
Mn......	7.35	+ .03	8.65	− .10	6.99	+ .07	6.19	+ .09	15.67	+ .03	14.37	+ .15	14.00	− .20
Fe......	7.80	+ .03	8.84	− .03	7.16	+ .04	6.56	+ .02	16.15	(+ .3)	15.11	(+ .3)	15.52	(+ .8)
Co......	8.25	.00	9.03	(.0)	7.32	+ .06	6.92	− .02	16.62	(+ .2)	15.84	(+ .2)	17.04	(+ .2)
Ni......	8.70	− .05	9.22	+ .08	7.48	+ .14	7.28	−0.06	17.09	+ .06	16.57	− .07	18.56	(− .4)
Cu......	9.15	− .20	9.41	+0.07	7.64	−0.01	......	......	17.56	+ .06	17.30	−0.21	20.08	(+0.2)
Zn......	9.60	−0.20	......	......	......	......	......	......	18.03	−0.10				

estimated values give an average residual of +0.20 volt (which perhaps indicates that the estimates are a little too high).

For the transition E, involving the removal of a 3d electron from a partially completed group, the constants of the formula are larger, and also the residuals, which average ±0.28 (including many estimated values). Though much more irregular, these are small enough to justify the explanation of the discontinuity given above.

PRINCETON
November 8, 1927

SECONDARY STANDARDS OF WAVE-LENGTH; INTERFEROMETER MEASUREMENTS OF IRON AND NEON LINES[1]

By HAROLD D. BABCOCK

ABSTRACT

After some discussion of the technique, standard wave-lengths are given for 286 iron lines, λ 3407–λ 6677, Table I, and for eleven neon lines, λ 5852–λ 6506, measured in terms of the primary standard, λ 6438.4696 of cadmium. The neon wave-lengths agree precisely with the values that have been adopted as secondary standards. Wave-lengths found for iron lines are systematically less than the adopted values, confirming results from other laboratories. From detailed comparisons it is concluded that the adopted system would be improved by a reduction of about 2 parts in 5,000,000 for wave-lengths less than λ 5506, and by a linear reduction in the red region amounting to 5 parts in 6,000,000 at λ 6200, and to 8 parts in 6,000,000 at λ 6600.

The systematic differences between the results of different observers are discussed and partially explained.

Table V gives a few additional wave-lengths obtained by the adjustment of earlier observations to the new scale. Table VI gives supplementary wave-lengths, λ 6213–λ 7586, for 63 iron lines observed under arc conditions somewhat different from those specified for the production of secondary standards.

I. INTRODUCTION

The development of the interference method of comparing wave-lengths by Fabry and Perot[2] and its subsequent extension and application by Fabry and Buisson,[3] Pfund,[4] Eversheim,[5] and others seemed to place the resulting system of secondary standards of wave-length[6] almost above criticism. Indeed, for fifteen years the most exacting tests have failed (except in the case of unstable lines), to reveal any errors as great as 2 parts in 1,000,000 in the adopted list of standard iron lines.

The observations of Meggers, Kiess, and Burns,[7] of Monk,[8] and

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 343.

[2] *Astrophysical Journal*, **15**, 73, 1902.

[3] *Comptes Rendus*, **143**, 165, 1906; **144**, 1155, 1907; *Astrophysical Journal*, **28**, 169, 1908.

[4] *Ibid*., p. 197, 1908.

[5] *Ibid*., **26**, 172, 1907; *Zeitschrift für wissenschaftliche Photographie*, **5**, 152, 1907.

[6] *Transactions of the International Astronomical Union*, **1**, 41, 1922.

[7] *Scientific Papers of the Bureau of Standards*, **19**, 263 (No. 478), 1924.

[8] *Astrophysical Journal*, **62**, 375, 1925.

the preliminary work of the writer[1] indicate, however, that a minute systematic adjustment would improve the adopted system of standards; and this is fully confirmed by the results now to be presented. The occasion for such an adjustment arises partly from the adoption[2] of new specifications for producing the iron spectrum, partly from improvements in the photography of the red part of the spectrum, and perhaps partly from the modern practice of transmitting the light of cadmium or of neon through the entire apparatus to the same plate which records the iron lines.

This paper describes details of the technique that has been followed and discusses a comparison of the results with those of other observers.

2. APPARATUS AND METHOD

The concave-grating spectrograph with interferometer attachment has previously been described,[3] but the grating itself and the plateholder were those to which reference has been made in a later paper.[4] A few plates were made with the aid of a small auxiliary spectrograph having a concave grating of 2-m radius mounted in parallel light. Seven pairs of planes were used in the etalons: some of fused quartz, some of glass, and one of crystalline quartz. Nine separators of either fused quartz or invar, ranging in thickness from 2.5 to 20 mm, served to keep the planes at fixed distances. Silver was usually sputtered on the planes to increase their reflecting power, but in a few cases gold was substituted.

Projection of an image of the source of light was accomplished by means of a concave mirror 40 cm in diameter and 46 cm in focal length, so arranged as to give about 7 diameters enlargement. Except for a vertical diametral strip 10 cm wide, the mirror was covered, since this reduces the radiation incident on the etalon to less than one-third of what it would be if the entire mirror were exposed, and still gives full illumination of the apparatus. A water-cell was generally placed before the etalon, and no radiation from the arc terminals was permitted to reach the etalon or its supports.

[1] *Physical Review*, Ser. 2, **25**, 716, 1925.

[2] *Transactions of the International Astronomical Union*, **1**, 36, 1922.

[3] *Mt. Wilson Contr.*, No. 137; *Astrophysical Journal*, **46**, 138, 1917.

[4] *Mt. Wilson Contr.*, No. 328; *Astrophysical Journal*, **65**, 140, 1927.

A distinct advantage is found in a strictly achromatic image of the source, accurately focused on the diaphragm of the etalon. This may be illustrated by comparison with the case of a quartz lens of 30-cm focal length used for projecting a fourfold magnified image of the arc on the interferometer. If such a lens is set to fulfil the foregoing condition for λ 5893, it is found that for λ 7200 the image is 6.3 cm from the interferometer, while for λ 3000 the image is 35 cm distant in the opposite direction. Further reference is made to this matter below.

It is customary to photograph lines of iron and of neon or cadmium on the same plate, by means of either divided or simultaneous exposures, or a combination of both. For example, ten photographs were made in the yellow-red region for which iron and neon spectra were simultaneous and cadmium was added by divided exposures. This was accomplished by projecting a real image of the neon lamp into the central region of the iron arc and again projecting the combined light by a concave mirror to the etalon. The concave mirror was mounted on a heavy iron table, capable of smooth rotation about a vertical axis and provided with a divided circle reading to one minute of arc. The cadmium lamp was situated symmetrically with respect to the combined iron and neon lamps, on the opposite side of the line joining etalon and concave mirror, so that nothing need be moved except the mirror, which required only a rotational displacement. Special care was taken to insure full illumination by each source separately.

In the case of other photographs the cadmium source was omitted, and the arrangement described above was used without moving the projecting mirror. Again, the neon and iron lamps were alternately projected on the etalon by rotation of the concave mirror, and in this case various schedules of exposure were followed, such as neon-iron-neon, iron-neon-iron, iron-neon-iron-neon- . . . ., etc. For all these cases the measurements showed no difference, a result dependent on the excellent stability of the apparatus and on the smallness of the variation in the etalons during the time of an exposure.

The iron arc was of the Pfund[1] type, and was used according to the latest specifications adopted by the International Astronomical

[1] *Astrophysical Journal*, 27, 297, 1908.

Union[1] for the production of secondary standards of wave-length. The anode was below, consisting of a large bead of iron oxide supported on the hollowed upper end of a vertical cylinder of iron or copper 15–20 mm in diameter. The cathode was a rod of steel 6 mm in diameter, fitted with a large cooling cylinder of brass just above its lower extremity. The cooler permitted only 2 or 3 mm of the cathode to project, and was always massive enough to prevent the formation of a pendant drop of metal or oxide on the cathode. Commercial Bessemer steel rod was generally used for the cathode, since it was less inclined than wrought iron or cold rolled steel to form molten oxide, which causes unsteadiness of the arc. The line voltage was 250, the current 4.5 amp, and the length of arc 12–18 mm. Light was taken only from a horizontal central zone perpendicular to the axis of the arc, not exceeding $1\frac{1}{4}$ mm wide.

When this type of arc is clean and correctly adjusted, it operates, in a quiet atmosphere, at a length of 15–18 mm with remarkable steadiness and freedom from clouds of oxide. About once an hour it is necessary to remove the accumulated deposit of oxide from the cooling cylinder on the cathode and to readjust the amount of iron rod protruding. The results obtained in this investigation confirm much previous experience with this arc in showing that it is practically free from pole effect.

The primary standard was obtained from a fused quartz vacuum tube operated on a 10,000-volt transformer at about 20 milliamperes, except in the case of two exposures for which a vacuum arc lamp was substituted. As the wave-lengths showed no difference, the cadmium arc exposures have been included with the others. The vacuum cadmium arc was operated on a 250-volt circuit at about 1 amp, and the pressure was kept near to 1 cm of mercury.

The spectrum of neon was obtained from lamps supplied by Adam Hilger, which operate on direct current at 200–220 volts and at 0.010 to 0.015 amp. Such lamps have been in use in our laboratory for several years and have proved highly satisfactory for spectroscopic purposes. The light is concentrated, steady, and of high intrinsic brightness, while the lines are sharp and very accurately reproducible in position. The strong line λ 6402 is reversed in some

[1] *Transactions of the International Astronomical Union*, 1, 36, 1922.

lamps of this type, and occasionally λ 6143 also, but the other lines appear unreversed under the resolving powers usually employed in precise measurements of wave-length, i.e., up to orders of interference of at least 60,000.

Photographic emulsions of various kinds were used for different parts of the spectrum. As the plates had to be cut into sections, each 12.5 cm long, in order to approximate to the focal surface, whose radius is 131 cm, it was customary to choose different emulsion for the various sections whenever the exposure could be shortened or simplified by their use. For the red, yellow, and green regions, Ilford Special Rapid Panchromatic plates were most frequently used, while for the blue and violet, Eastman Contrast Bromide plates were found most satisfactory. Color screens were frequently helpful in making the density of the photographs more uniform throughout their length.

The method of measurement and reduction of the photographs scarcely needs further description. Reference may be made to previous *Contributions*[1] for the details. Most of the results were obtained from photographs, each covering 2000 A, which were treated like those described in the last of these references.

Correction for change of phase was made by the method of two etalons of different thickness in which the same planes were mounted successively. Occasionally the two photographs obtained in this way were reduced by the difference method to a single set of wave-lengths without actually evaluating the amount of the correction. This method, described by Merrill,[2] consists in determining the two thicknesses from the standard cadmium line and dividing the difference of the thicknesses by the differences of the orders of interference for the individual iron lines. Such results obviously require no correction for change of phase.

Corrections for dispersion of the atmosphere were nearly always negligible, but when required were taken from the tables published for the purpose by the Bureau of Standards.

Most of the photographs were measured by one observer; a few

[1] *Mt. Wilson Contr.*, Nos. 137, 202, 328; *Astrophysical Journal*, **46**, 138, 1917; **53**, 260, 1921; **65**, 140, 1927.

[2] *Scientific Papers of the Bureau of Standards*, **14**, 159 (No. 302), 1917.

of them by a second; and still others, with some duplication, by a third. The absence of appreciable personal equation in the results is shown by the accordance of the separate reductions of the same material.

In such delicate observations as those required for determining standards of wave-length, the greatest difficulty, in my experience, is the fulfilment, during an exposure, of certain optical conditions in the apparatus. In comparison, the difficulties of measurement and reduction are almost negligible, provided the interference pattern is properly photographed on a sufficiently large scale. For an illustration, I am indebted to my son Horace, a high-school student, who, during the first hour of his measurement of spectra, obtained results for typical iron and neon lines differing less than 0.001 A from those which had been obtained from the same plate by an experienced observer.

Some of the optical requirements are: (1) planeness and parallelism of the etalon plates; (2) coincidence of normal at center of etalon with optical axes of the projection systems which precede and follow it and also with that of the co[illegible]ator of the spectrograph; (3) correct focus for each projection system and for the spectrograph throughout the whole extent of spectrum covered by each photograph; (4) projection, in focus on the grating, of a real image of the diaphragm which limits the etalon; (5) freedom from astigmatism and from variation of magnification over the whole field covered by the camera of the spectrog[illegible] reduction of total radiation incident on the etalon [illegible]imum by diaphragms and screens.

Throughout the investigation strict attention has been given to such conditions, and the correct position of each part of the system has been repeatedly verified. As noted above, seven pairs of planes have been used to make the etalons. These have always been adjusted to parallelism over a much larger aperture than is actually used for making a photograph. If left to themselves, they would remain in adjustment long after the completion of the photograph for which they were prepared.

The third condition, when a long range of spectrum is to be observed at one time, is not so easy to meet as might appear, and de-

parture from it may introduce small systematic errors. If the image produced by the projection system is not in focus on the etalon, it is evident that some mixing of light from different parts of the source will occur, and in the case of the iron arc a departure from the specifications may result. In addition, the interference pattern may show a difference of brightness on opposite sides of the center, particularly in the red region where the arc is far more intense near the cathode than anywhere else.

Imperfect focus of the projector which puts the interference pattern on the slit may be an insidious source of small errors. For example, a certain spectrograph has a focal surface for dust lines which is closely represented by a circle of radius 131 cm. If an interference pattern is projected on its slit by a well-corrected triplet lens of 41-cm focal length adjusted for red light, the rings for λ 4000 will be in focus 2 mm behind the slit and the resultant focal surface for the rings will deviate by that amount from the true focal surface of the spectrograph. The use of concave mirrors throughout is a satisfactory solution of these difficulties.

The fourth condition, long ago pointed out by Fabry and Buisson,[1] appears often to have been overlooked. Yet it is essential for exact equivalence of the various ring segments of a given line. In this investigation the image of the diaphragm has always been made smaller than the ruled surface of the grating and sharply focused thereon, so that the portion of the etalon actually used is all of that defined by the diaphragm in front of the etalon, and is the same for every ring segment photographed. Disregard of this condition may easily lead to non-uniformity of intensity in the ring segments for each line, as well as to small differences of fractional order for inner and outer rings. Without more complete data regarding the apparatus used by other observers, it is impossible to determine the effect on their results of ignoring this detail; but from their published descriptions it would appear to be a possible explanation of some of the discrepancies noted below.

The fifth condition was examined in detail for my apparatus by measurements of photographs taken without the interferometer, but with a series of small apertures over the slit. No distortion was found

[1] *Journal de physique*, **7**, 169, 1908.

on any part of the plate, although the tests would easily have shown its presence.

It is evidently desirable to reduce the time of exposure as much as possible for work of this exacting nature, in order to minimize the effects of earth tremors and inevitable small changes of temperature produced by exposing the etalon to the radiation of the arc. With a grating having remarkably high intensity in the red end of one first-order spectrum, the average time elapsing during a complete observation in the region λ 6200 was forty minutes, and for shorter wave-lengths it was still less. Comparison shows that in general other observers have required considerably longer intervals for the completion of an observation.

An important feature of the equipment used here is the concave mirror which projects the interference pattern on the slit. Highly perfect in figure, of 10-cm aperture, 63-cm focal length, and capable of precise adjustment, it provides accurate images of the rings for all wave-lengths on a large uniform scale. The aperture of the mirror actually used in the observations is of course determined by the size of the diaphragm on the etalon and the angular aperture of the projector which illuminates the etalon. An advantage resulting from the long focus of this mirror is the ease with which the maxima of the lines may be discerned on the photographs, with consequent freedom from systematic errors dependent on the width of the spectral lines. If all spectral lines were of equal width, no error would be introduced by measuring the geometrical centers instead of the maxima of the ring segments; but in the actual case appreciable differences may enter, which generally tend to make iron lines appear to have wave-lengths too long when they are compared with standards from neon and cadmium. Settings have always been made on the maxima of intensity of the lines, and thorough examination has failed to show any effects which depend on width or intensity. Furthermore, the differences in fractional order found from inner and outer rings are quite small and purely accidental in character.

The difficulty of maintaining high resolving power for violet light, without serious loss of intensity for red light, is an inherent limitation of the interferometer provided with silver films. For this reason not all the observed iron lines of wave-length less than λ 4271 were

directly compared with the neon or cadmium standards; 18 of them were measured in terms of nearby iron lines, while 45 others were compared with both iron and neon standards. The lines so dealt with are referred to in a following paragraph.

3. RESULTS

The first column of Table I gives the wave-lengths which have been found for 286 iron lines. The second column indicates the number of plates on which each line was measured; the third gives the intensity assigned by Meggers, Kiess, and Burns[1] and also the pressure group of the Mount Wilson classification, revised in some cases with the aid of new data on the pressure effect. In the last column is found the multiplet designation, based on the papers of Walters,[2] Meggers,[3] and Laporte,[4] with additions from the unpublished list of term values prepared by Professor Russell and Miss Moore.

Wave-lengths marked with two asterisks were derived, not from the standards of neon and cadmium, but, for the reason indicated above, by comparison with nearby iron lines. The lines marked by a single asterisk were measured partly in this way and partly in terms of neon standards. For such lines no difference appeared between the results of the two procedures; and since the lines marked** occurred on photographs thus controlled, they have been included in Table I, and, in fact, are as well determined as the rest of the lines in the table.

The uniformity of the results from separate plates is illustrated in Table II, which gives for a few points in the spectrum the respective values for each plate measured. The corresponding average probable error of a mean wave-length is ± 0.0002 A, and of a single determination, ± 0.0008 A. The same order of accuracy is found throughout Table I, for lines of pressure groups *c* and *d* as well as for those of groups *a* and *b*. The probable error of any wave-length in Table I may therefore be found by dividing ± 0.0008 A by the square root of the number of plates measured. For all lines except those meas-

[1] *Loc. cit.*

[2] *Journal of the Optical Society of America*, **8**, 245, 1924.

[3] *Astrophysical Journal*, **60**, 60, 1924.

[4] *Proceedings of the National Academy of Sciences*, **12**, 496, 1926.

ured on only one or two plates, the probable errors of the wave-lengths are evidently well under ± 0.0005 A, and the fourth decimal place might have been retained with some justification. But the actual uncertainty is always greater than the probable error, and it appears better to omit the fourth place because of the probability of undetected systematic errors affecting this figure.

Eleven prominent neon lines between λ 5852 and λ 6506 were determined in terms of the primary standard from ten excellent photographs made with etalons ranging in thickness from 2.5 to 20 mm. The photographs were reduced by the method of differences referred to above, so that the wave-lengths are independent of any other observations. Except for two lines, the results are identical with the adopted wave-lengths of standard neon lines. For these exceptions my wave-lengths are 5852.487 and 6266.494, while the adopted values are 5852.488 and 6266.495, respectively. For the first of these Monk[1] found 5852.487. Since these photographs also show the iron-arc spectrum, exposed simultaneously with neon and referred in the same way to the primary standard, it seems reasonable to believe that the wave-lengths for the red iron lines are correctly determined. Moreover, wave-lengths for the same red iron lines, derived independently from neon standards on other plates, show no systematic difference from the results obtained from the ten plates referred to here.

4. DISCUSSION

A comparison of the wave-lengths in Table I with the system of secondary standards adopted by the International Astronomical Union[2] shows that the new values are systematically smaller. If unstable lines are omitted from the comparison, the differences, from the beginning of the table to λ 5506, are very uniform, averaging 0.0023 A for thirty-nine standards. A similar comparison with the "interpolated" wave-lengths[3] of the secondary standards gives the same average difference. For seventeen unstable secondary standards in this region of the spectrum the corresponding differences are 0.0094 and 0.0095 A, respectively, but if the new wave-lengths for

[1] *Loc. cit.*

[2] *Transactions of the International Astronomical Union*, 1, 41, 1922.

[3] *Ibid.*

these unstable lines are compared with the former Mount Wilson values[1] alone, instead of with the interpolated results, the mean difference becomes 0.0022 A, i.e., identical with the difference for stable lines. This clearly illustrates the reproducibility of the arc used at this Observatory, and indicates a mean pole effect of 0.007 A for these unstable secondary standards in the arcs which were originally used for producing them.

From the ultra-violet to the yellow the results in Table I are uniformly less than the adopted system of standards; an adjustment of 0.002 A will harmonize the two systems satisfactorily, if only stable lines are considered. For the spectral region λ 6065–λ 6750 the new values are also systematically less than the adopted system; but here, instead of being uniform, the difference increases with the wave-length. In fact, if the individual differences are plotted as ordinates against wave-lengths as abscissae (Fig. 1), the points lie throughout on a straight line with only one deviation as great as 0.001 A. The average amount of the difference is 0.0086 A.

A comparison of my measurements with those of Meggers, Kiess, and Burns,[2] the spectrum being divided into two parts as before, shows that for 80 lines, λ 3513–λ 5506, my wave-lengths are systematically shorter than theirs. The differences Babcock *minus* Meggers, Kiess, and Burns are positive for 2 lines, zero for 12, and negative for 66, with an average of −0.0013 A. From λ 6065 to λ 6677 there are 2 zero differences, 1 positive and 17 negative, with an average of −0.0022 A. Since for the red lines all the corrections usually become negligible and since these lines show the same consistency among individual measurements as lines of shorter wave-length, it is at first surprising to find a greater systematic difference in this part of the spectrum. Examination of the paper of Meggers, Kiess, and Burns shows, however, that although the title says clearly that their work was done with the new international arc, i.e., the arc specified by the International Astronomical Union in 1922, the description of the apparatus indicates that they did not use the specified arc. On page 264 they say: "Iron rods 7 mm in diameter were used as electrodes and the upper or positive pole was surrounded by

[1] *Loc. cit.;* also *Mt. Wilson Contr.*, No. 202; *Astrophysical Journal*, **53**, 260, 1921.

[2] *Scientific Papers of the Bureau of Standards*, **19**, 263 (No. 478), 1924.

a close fitting brass cylinder perforated with holes to serve as a radiator." In the Pfund arc, however, the negative pole and the

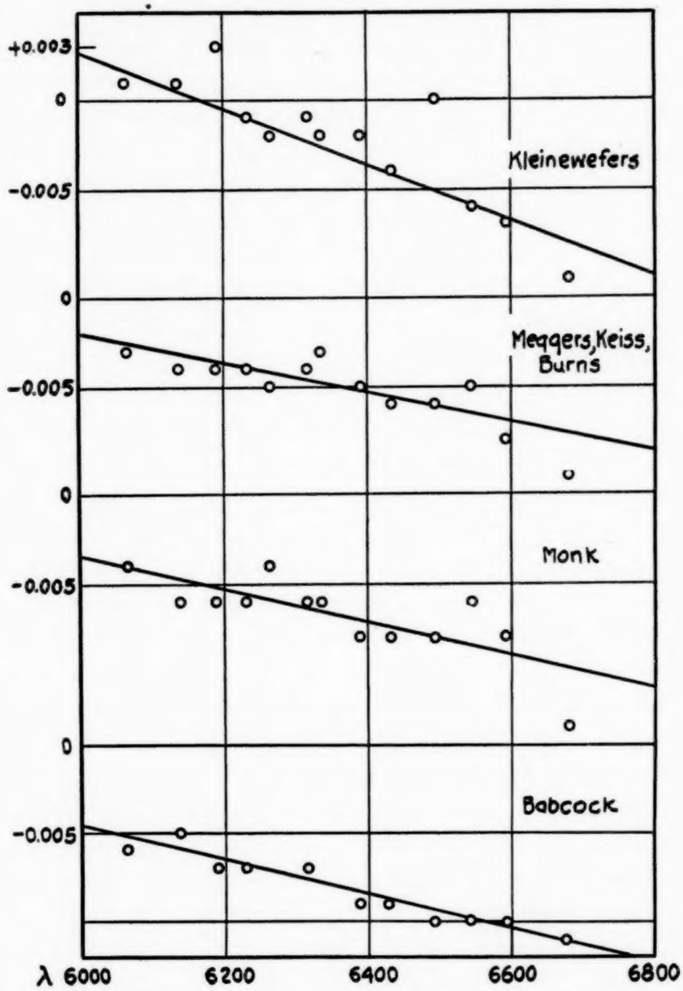


FIG. 1.—Comparison of recent measurements with adopted system of secondary standards in the red region. The horizontal line marked o above each observer's name represents the secondary standards. Small circles indicate the departures (unit = 1 A) for individual spectral lines.

attached cooling cylinder are above, while below is a massive rod of iron or copper, 10–15 mm thick, the actual anode being a bead of iron

oxide resting in the hollowed upper end. The differences indicated may appear slight, but they are in fact of real significance. Essential features of the Pfund type of arc are the polarity and the provisions made to prevent overheating of both terminals.

After discovering the systematic difference in the red region referred to above, I set up the same kind of arc as that described by Meggers, Kiess, and Burns and measured the red lines in exactly the same way as I had done previously with the specified arc. The results were confirmed on a second plate, and the means for 6 lines are on the average the same as the wave-lengths obtained by them.

Although it is not insisted that the entire systematic difference between my results and those of Meggers, Kiess, and Burns is caused by real differences in wave-length in the sources used, it would seem possible that such an explanation may account for part of the difference. This is confirmed by a comparison of our wave-lengths for 26 sensitive lines of groups *c* and *d*, which give a mean difference, Babcock *minus* Meggers, Kiess, and Burns, of −0.0023 A, instead of −0.0011 A, as for the stable lines. Here is found evidence that the arc used by them exhibits pole effect to the extent of about 0.001 A, and it might therefore be expected that the red *b* lines would show wave-lengths slightly too great when observed in their arc.

It may be remarked here that the observations of St. John and Babcock[1] on pole effect in the iron arc were made with arcs about 6 mm long. The measurements were differential, i.e., they showed the change in wave-length for each line when observed at the pole and at the center; but they failed to show the amount of pole effect still existing at the center of the arc. For the red *b* lines the measurements did indeed show slight apparent displacements toward the red at the negative pole, but of a magnitude too small to be distinguished from errors of observation. On this basis the lines were classed as stable, but later experience has shown them to be somewhat unstable, though far less so than nearby lines of group *d*. If in our early observations of pole effect we had compared negative pole and center of such an arc as the one now used for producing secondary standards, we probably would have found definite displacements of a few thousandths of an angstrom for the red *b* lines.

[1] *Mt. Wilson Contr.*, No. 106; *Astrophysical Journal*, **42**, 1, 1915.

Comparison of my wave-lengths with those of Monk[1] shows that the difference Babcock *minus* Monk is systematically negative. For 85 lines of all groups there are 7 positive, 18 zero, and 60 negative differences, the average being −0.0010 A. Practically no distinction appears between stable and unstable lines, nor between various spectral regions. Since the arc used by Monk was the same as mine, the slight systematic difference in our results is probably caused by some small difference in technique at present unrecognized. It appears unlikely that this should be connected with the correction for change of phase, for the difference is nearly uniform throughout a long range of spectrum, including that part where all corrections become zero.

The work of Wallerath[2] contains only 9 lines in common with Table I of this paper. For these the difference Babcock *minus* Wallerath is negative in every case, and the average is −0.0024 A. The lines compared are scattered over the region λ 3513–λ 5341 and are all stable. Kleinewefers,[3] working with practically the same apparatus as Wallerath, obtained wave-lengths for iron lines from λ 5167 to λ 6677, including 40 which are found in Table I. For an examination of the differences between his results and mine, the spectrum may be divided into two parts, λ 5167–λ 5658 and λ 6065–λ 6677. In the first part the differences Babcock *minus* Kleinewefers for 16 stable lines are all negative except two, one of which is zero, the other positive. The mean of these is −0.0021 A. Eleven lines of group *d*, however, all show negative differences averaging −0.0049 A, a definite indication of pole effect in the arc used by Kleinewefers. For 13 red *b* lines the differences, all negative, average −0.0057 A, but they range from −0.001 to −0.010 A in an irregular manner. In Figure 1, to which reference has already been made, the results, for the red *b* lines, of Meggers, Kiess, and Burns, Monk, Kleinewefers, and Babcock, are graphically compared with the adopted system of secondary standards.

The preceding paragraphs give comparisons of my results with those of other observers. It will be instructive to summarize for these observers the deviation of their wave-lengths from the inter-

[1] *Astrophysical Journal*, **62**, 375, 1925.

[2] *Annalen der Physik*, **75**, 37, 1924.

[3] *Zeitschrift für Physik*, **42**, 211, 1927.

TABLE I

STANDARD WAVE-LENGTHS OF IRON ARC LINES

λ	No. Plates	Intensity	Group	Multiplet
**3407.461	5	7	*d*	D–x
**3413.133	3	7	*d*	D–x
**3427.120	5	6	*d*	D–x
**3443.878	5	6	*a*	A–H
**3465.862	5	6R	*a*	A–H
**3476.704	5	5r	*a*	A–H
**3490.575	5	6	*a*	A–H
*3497.843	6	5r	*a*	A–H
*3513.819	6	5	*b*	B–M
*3521.264	6	5r	*b*	B–M
3541.087	1	6	....	....
3542.079	1	5	*d*	V–y
*3554.929	7	8	....	....
*3558.518	8	5r	*b*	B–M
3581.196	2	8R	*b*	B–L
3584.664	2	5	....	....
3585.321	8	6r	*b*	B–L
3586.114	2	5	....	....
3586.986	6	6	*b*	B–L
3589.108	2	4	*b*	B–L
3603.206	2	5	*d*	V′–U‴
3605.454	2	5	*d*	V′–U‴
*3606.682	6	5	*d*	V′–U‴
*3608.862	8	6R	*b*	B–L
3610.163	2	5	*d*	V–y ?
3617.788	2	6	*b*	....
*3618.769	6	6R	*b*	B–L
3621.464	2	6	....	....
3622.005	2	6	*d*	V′–U‴
*3631.465	5	6R	*b*	B–L
3638.301	2	6	*d*	V′–U‴
3640.391	2	6	*d*	V′–U‴
*3647.843	6	6R	*b*	B–L
3649.508	2	6	....	....
3651.470	2	6	*b*	....
3669.524	2	6	*b*	....
3677.630	2	6	....	....
*3679.915	13	5r	*a*	A–G
3683.056	2	4	*a*	A–G
3686.000	2	5	*e*	W–y
3687.459	10	6R	*b*	B–K
3689.460	2	6	....	....
3694.010	2	6	....	....
3695.053	1	3	*b*	....
3701.090	2	6	*d*	W–y

TABLE I—*Continued*

λ	No. Plates	Intensity	Group	Multiplet
3704.463	2	5	*b*	....
*3705.567	15	6R	*a*	A–G
3707.048	1	3	*d*	W–y
*3709.248	19	6	*b*	B–K
3716.447	2	6	....	....
**3719.937	3	8R	*a*	A–G
*3722.563	16	6R	*a*	A–G
*3727.621	18	6R	*b*	B–K
3732.398	2	6	*b*	....
*3733.318	13	6R	*a*	A–G
**3737.134	3	7R	*a*	A–G
3738.306	2	4	*b*	....
*3743.364	18	6	*b*	B–K
**3748.264	3	6R	*a*	A–G
**3749.487	3	8R	*b*	B–K
3753.612	2	6	*d*	D–S
*3758.234	4	7R	*b*	B–K
3760.050	2	5	*b*	....
*3763.791	10	6R	*b*	B–K
3765.541	2	6	*b*	....
*3767.193	18	6R	*b*	B–K
3787.882	13	6R	*b*	B–K
3790.095	2	4	*b*	B–K′
*3795.004	19	6r	*b*	B–K
3797.517	2	5	*b*	....
*3798.513	14	6r	*b*	B–K
*3799.549	15	6r	*b*	B–K
3805.344	2	6	*b*	....
3806.698	2	6	*d*	....
3807.538	2	4	*d*	D–S
*3812.966	15	6	*b*	B–K′
*3815.842	10	7R	*b*	C–P
**3820.428	3	8	*b*	B–J
3821.181	2	6	*d*	....
*3824.445	11	6R	*a*	A–F
**3825.884	3	8R	*b*	B–J
*3827.824	18	6R	*b*	C–P
3834.224	14	7R	*b*	B–J
3836.332	1	3	....	....
3839.258	2	5	....	....
3840.439	9	6R	*b*	B–J
3841.049	9	6R	*b*	C–P
3843.258	2	5	*b*	....
3846.802	2	5	*b*?	....
*3849.969	15	5	*b*	B–J

TABLE I—*Continued*

λ	No. Plates	Intensity	Group	Multiplet
3850.820	2	5	*b*	B–K′
3852.574	2	3	*d*	D–S
*3856.373	9	6R	*a*	A–F
3859.214	2	5	....	....
*3865.525	16	6R	*b*	B–J
3867.218	2	3	*b*	....
*3872.503	18	6r	*b*	B–J
3873.762	2	4	*b*	....
*3878.020	12	6r	*b*	B–J
3878.574	9	6R	*a*	A–F
3885.512	2	3	*b*	....
**3886.284	3	7R	*a*	A–F
*3887.050	12	6r	*b*	B–J
*3888.516	14	7	*b*	C–P
3893.391	2	4	....	....
*3895.658	19	5r	*a*	A–F
*3899.708	20	6r	*b*	A–F
3902.948	14	7r	*b*	C–P
*3906.481	9	5r	*a*	A–F
3907.937	1	3	*b*	....
3916.733	1	3	*b*	....
3917.184	2	5	*b*	B–J
*3920.259	19	6r	*a*	A–F
*3922.913	20	6R	*a*	A–F
*3927.921	18	6r	*a*	A–F
*3930.298	18	7R	*a*	A–F
3935.814	1	4	*b*	....
3940.880	2	4	*b*	B–J
3942.442	1	3	*b*	....
3948.778	2	4	*b*	....
3949.954	2	4	*d*	D–X′
3951.164	2	4	*b*	....
3952.606	1	4	*d*	V′–U′
3956.680	2	4	*d*	V′–U′
3966.064	2	7	*b*	C–P
3967.424	1	4	*b*	....
*3969.260	17	7r	*b*	C–N
3971.325	2	4	*d*	V′–x
3977.743	2	5	*d*	D–X′
3983.960	2	5	*d*	V′–x
3997.394	2	6	*d*	V′–U′
3998.054	2	5	*d*	V′–x
4005.244	12	7	*b*	C–N
4009.714	2	5	*d*	D–X′
4014.534	2	4	*b*	....

TABLE I—*Continued*

λ	No. Plates	Intensity	Group	Multiplet
4021.869	2	5	*d*	V′–U′
*4045.814	8	8R	*b*	C–N
4063.597	13	8	*b*	C–N
4071.741	12	7	*b*	C–N
**4132.061	4	7	*b*	C–N
**4143.871	5	7	*b*	C–N
**4202.032	5	7r	*b*	C–M
4233.608	5	6	*d*	E–X
4235.942	2	8	*d*	E–X
4238.816	3	4	*d*	....
4245.258	3	2	*b*	....
4247.432	1	5	*d*	....
*4250.790	6	8	*b*	C–M
*4260.480	5	10	*d*	E–X
4267.829	1	2	*b*	....
**4271.764	5	8r	*b*	C–M
4282.406	7	6	*a*	D–Y
4285.444	3	2	*b*	....
4291.466	1	1	*a?*	....
4294.128	6	6	*b*	C–L
4299.242	5	7	*d*	E–X
4305.455	3	2	*b*	....
4307.906	4	8r	*b*	C–M
4315.087	9	5	*a*	D–Y
4325.765	2	9r	*b*	C–M
4337.049	9	5	*b*	C–L
4352.737	8	4	*a*	D–Y
4369.774	6	3	*b*	....
4375.932	8	5	*a*	A–V
4383.548	3	10R	*b*	C–L
4390.956	2	3	*b*	....
4408.418	1	4	*c*	D–Q
4415.125	2	8r	*b*	C–L
4422.570	6	4	*b*	....
4427.311	8	5	*a*	A–V
4430.618	3	4	*c*	D–Q
4442.342	4	5	*c*	D–Q
4443.198	2	3	*b*	....
4447.721	5	5	*c*	D–Q
4454.383	4	3	*b*	....
4459.121	5	5	*c*	D–Q
4461.654	5	4	*a*	A–V
4466.554	9	5	*b*	....
4469.381	1	4	*d*	....
4476.021	8	7	*b*	....

TABLE I—*Continued*

λ	No. Plates	Intensity	Group	Multiplet
4484.227	1	3	*d*	H–T′
4489.740	4	3	*a*	A–V
4494.567	7	5	*c*	D–Q
4525.142	1	3	*d* ?	....
4528.618	5	7	*c*	D–Q
4531.152	9	5	*b*	C–K
4547.850	4	3	*b*	....
4592.655	5	4	*b*	C–K
4602.944	7	4	*b*	C–K
4611.285	1	4	*d*	....
4625.052	1	4	*d*	F–U
4647.436	6	4	*b*	....
4667.459	5	4	*b* ?	....
4678.851	4	5	*b* ?	....
4691.414	4	4	*b* ?	....
4707.280	5	5	*d*	F–U
4710.286	4	3	*b*	....
4733.595	4	3	*b*	C–J
4736.780	12	5	*d*	F–U
4745.805	1	3	*b*	....
4772.816	2	3	*b*	C–J
4786.809	2	3	*b*	....
4789.652	5	3	*b*	....
4859.747	9	5	*d*	V–X
4871.323	5	8	*d*	V–X
4872.144	5	6	*d*	V–X
4878.217	5	5	*d*	V–X
4891.496	2	9	*d*	V–X
4903.316	3	5	*d*	V–X
4918.999	7	8	*d*	V–X
4920.509	8	10	*d*	V–X
4957.603	1	10	*d*	V–X
4966.094	1	5	*d*	G–U
4994.133	1	3	*a*	B–G
5006.126	2	5	*d*	V–X
5012.071	11	4	*a*	B–G
5049.824	7	5	*b*	D′–P
5051.637	6	4	*a*	B–G
5083.342	2	4	*a*	B–G
5110.414	5	4	*a*	A–E
5167.490	9	8	*a*	C–Z
5168.899	1	3	*a*	A–E
5171.599	14	7	*a*	C–I
5192.350	9	8	*d*	W–X
5194.943	7	5	*a*	C–I

TABLE I—*Continued*

λ	No. Plates	Intensity	Group	Multiplet
5202.339	3	5	*b*	D–O
5216.276	6	5	*a*	C–I
5227.191	7	8	*a*	C–Z
5232.946	10	8	*d*	W–X
5266.562	10	8	*d*	W–X
5269.541	4	10	*a*	B–F
5270.359	8	8	*a*	C–Z
5281.796	2	5	*d*	W–X
5283.628	6	7	*d*	F–T
5302.307	2	5	*d*	F–T
5324.185	10	6	*d*	F–T
5328.042	5	4	*a*	B–F
5339.935	1	3	*d*	F–T
5341.025	20	5	*a*	C–Z
5364.874	1	3	*e*	L–λ
5367.470	2	3	*e*	L–L′
5369.965	3	4	*e*	L–L′
5371.493	9	7	*a*	B–F
5383.374	5	5	*e*	L–λ
5393.174	6	4	*d*	F–T
5397.130	17	6	*a*	B–F
5404.144	1	3	*e*	L–L′
5405.777	12	6	*a*	B–F
5410.913	2	3	*e*	....
5415.201	5	4	*e*	L–L′
5424.072	4	4	*e*	L–L′
5429.699	10	6	*a*	B–F
5434.526	22	6	*a*	B–F
5446.919	11	6	*a*	B–F
5455.613	15	6	*a*	B–F
5497.518	22	4	*a*	B–F
5501.468	17	4	*a*	B–F
5506.782	23	4	*a*	B–F
5554.895	2	3	*e*	....
5563.604	2	3	*d*	J–T′
5565.708	2	3	*e*	....
5569.624	2	5	*d*	G–T
5572.848	3	5	*d*	G–T
5586.761	4	6	*d*	G–T
5615.650	4	6	*d*	G–T
5624.548	2	5	*d*	G–T
5638.266	1	3	*d*	K–T′
5658.825	2	4	*d*	G–T
5662.524	2	3	*d*	K–T′
6065.486	25	4	*b*	c–N

TABLE I—*Continued*

λ	No. Plates	Intensity	Group	Multiplet
6136.618	26	4	*b*	v–M
6137.696	20	4	*b*	c–N
6191.561	26	5	*b*	v–M
6230.727	23	5	*b*	c–N
6252.559	16	4	*b*	v–M
6318.021	6	4	*b*	v–L
6393.603	19	5	*b*	v–L
6400.010	7	5	*d*	H–T
6421.354	10	4	*b*	D′–K′
6430.850	14	5	*b*	D–J
6494.983	20	5	*b*	v–L
6546.242	9	3	*b*	V′–N
6592.918	9	5	*b*	V′–N
6677.993	2	5	*b*	V′–N

polated[1] wave-lengths for stable lines in the range λ 3370–λ 5506, since a greater amount of material is thus available for comparison, and since the interpolated system is on the average identical with the adopted system of secondary standards. This is done in Table III.

The agreement of the last three means is probably as close as can be expected. They show systematic differences of only 1 part in 10,000,000, but little more than the probable errors of the observations. Taken together they seem to outweigh the first two for several reasons: (1) number of lines observed; (2) the last three are entirely independent results, while the first two depend on work done in the same laboratory with practically identical apparatus and technique; (3) results obtained with the same apparatus by Eversheim differ systematically from those of other observers, in the same direction[2] that those of Wallerath and Kleinewefers differ from the others in Table III.

The arithmetical mean of the five average differences is +0.0010 A; if the first two are combined and weights proportional to number of lines involved are assigned, the weighted mean is +0.0015 A; if the first two are omitted, the weighted mean is +0.0017 A. It appears

[1] *Loc. cit.*

[2] Priest, *Physical Review*, Ser. 1, **31**, 602, 1910.

safe to conclude that the adopted system of standards would be improved by a reduction of about 2 parts in 5,000,000 for wave-lengths

TABLE II

AGREEMENT OF SEPARATE DETERMINATIONS

	λ 3585	λ 4466	λ 5012	λ 5506	λ 6230	λ 6494
	.321	.553	.070	.780	.727	.982
	.321	.553	.070	.782	.726	.982
	.321	.555	.071	.783	.726	.982
	.320	.554	.070	.780	.726	.983
	.321	.554	.070	.780	.727	.983
	.321	.555	.072	.781	.724	.985
	.321	.556	.072	.780	.725	.982
	.320	.554	.072	.782	.725	.983
		.555	.071	.781	.729	.982
			.070	.782	.727	.982
			.070	.782	.729	.984
				.781	.728	.984
				.781	.728	.984
				.781	.728	.984
				.782	.728	.985
				.782	.728	.984
				.781	.728	
				.782	.726	
				.784	.729	
				.784		
				.782		
				.782		
				.782		
Means......	.321	.554	.071	.782	.727	.983

TABLE III

AVERAGE DIFFERENCES FOR STABLE LINES BETWEEN λ 3370–λ 5506

Comparison	Difference	No. Lines
Interpolated – Wallerath..................	+0.0000 A	30
Interpolated – Kleinewefers..............	.0002	17
Interpolated – Meggers, Kiess, Burns......	.0014	95
Interpolated – Monk......................	.0015	73
Interpolated – Babcock..................	+0.0019	187

less than λ 5506, and by a linear reduction in the red region amounting to about 5 parts in 6,000,000 at λ 6200 and about 8 parts in 6,000,000 at λ 6600.

It may be pointed out that Table I closely confirms the preliminary results[1] obtained with the same apparatus, and that the final

[1] *Ibid.*, Ser. 2, **25**, 716, 1925.

wave-lengths given here for the red iron lines have been tested in actual use. Precise wave-lengths of oxygen absorption lines[1] have been derived in terms of these iron wave-lengths and independently from the neon standards. Both reference systems gave the same results for oxygen.

A summary of the features of this investigation which tend to reduce the number and magnitude of systematic errors would include: (1) reduced time of exposure; (2) photographs of large scale, both in the interference pattern and in the auxiliary dispersion; (3) reduced number of optical parts in the system; (4) large number of etalon plates successively employed; (5) variety of methods of exposing to the different sources; (6) achromatic projection throughout; (7) rigorous tests for correct adjustment of the entire optical system; (8) absence of systematic difference in fractional orders from inner and outer rings; (9) freedom from effects depending on width and intensity of the lines and on personal equation in the measurements; (10) freedom from pole effect in the iron arc.

During the progress of the work described here the same apparatus has been used for observations of wave-lengths from the vacuum iron arc, which will be discussed in a forthcoming paper. It is interesting to note that the dispersion among the results for the same line from individual plates is practically the same for the vacuum arc as for the open arc specified for producing secondary standards. There is no evidence of greater reproducibility or of higher attainable accuracy in the spectrum from the vacuum arc—a conclusion in agreement with that of Monk.[2]

For wave-lengths shorter than λ 5506, the work of St. John and Babcock[3] was done with the long Pfund arc under the same conditions as have been observed in obtaining the data of Table I. Lines measured by them but not included in Table I may readily be revised to the present scale by applying small corrections derived by comparing material common to the two lists. These corrections are summarized in Table IV. Since the corrections cover a range of only

[1] Dieke and Babcock, *Mt. Wilson Communications*, No. 102; *Proceedings of the National Academy of Sciences*, **13**, 670, 1927.

[2] *Loc. cit.*

[3] *Mt. Wilson Contr.*, No. 202; *Astrophysical Journal*, **53**, 260, 1921.

0.002 A throughout the region discussed, it appears that the wave-lengths relative to each other were determined almost as accurately

TABLE IV

CORRECTIONS TO BE APPLIED TO EARLIER MOUNT WILSON WAVE-LENGTHS OF IRON LINES

Region	No. Lines	Mean Correction
3407–3589	20	−0.0009 A
3603–3695	23	.0010
3701–3799	28	.0017
3805–3899	35	.0017
3902–3997	22	.0021
4005–4299	26	.0020
4305–4447	18	.0021
4454–4691	21	.0032
4707–4994	19	.0029
5001–5283	21	.0023
5302–5506	23	−0.0025

in 1921 as they have been in the recent measurements. A few lines, chiefly secondary standards not included in Table I, have been re-

TABLE V

CORRECTED WAVE-LENGTHS OF CERTAIN IRON LINES MEASURED IN 1921

λ	No. Plates	Intensity	Group	Multiplet
3370.787	13	6	....	....
3399.336	20	6	*d*	D–x
3445.151	25	4	*d*	D–x
3485.341	14	6	*d*	D–a
3536.558	26	6	....	....
3565.381	39	6R	*b*	B–M
3676.313	29	6	....	....
3724.378	26	6	....	....
4095.975	17	3	*b*	....
4107.492	25	5	*b*	....
4118.549	37	6	*b*	....
4134.682	37	5	*b*	....
4147.674	40	4	*b*	C–M
4175.640	56	4	*b*	....
4184.895	52	4	*b*	....
4203.987	36	3	*b*	....

duced to the new scale by means of these average corrections and are listed in Table V.

In addition to the new measurements and the revision of certain

TABLE VI

SUPPLEMENTARY MEASUREMENTS; PROBABLY MODERATE POLE EFFECT

λ	No. Plates	Intensity	Group	Multiplet	Meggers and Kiess
6213.438	3	3	*b*	D–J	.435
6219.290	3	3	*b*	D–J	.286
6240.656	1	2	*b*	D–K	....
6254.262	2	3	*b*	D–K′	.262
6256.370	2	3	*b*	v–M	.366
6265.139	3	3	*b*	D–J	.140
6280.625	2	2	*a*	B–V	.621
6290.968	1	3	*e* ?	P–g	....
6297.800	2	3	*b*	D–J	.800
6322.693	3	3	*b*	c–N	.693
6335.338	2	4	*b*	D–J	.338
6336.835	2	4	*d*	H–T	.841
6344.154	2	2	*b*	v–M	.155
6355.038	2	3	*b*	c–P	.037
6358.692	2	3	*a*	B–V	....
6380.748	2	3	*b*	....	.748
6408.031	3	4	*d*	H–T	.034
6411.658	3	4	*d*	H–T	.666
6462.731	3	4	*a*	B–V	.732
6469.214	1	4	*b*	v–L ?	....
6475.632	2	3	*b*	c–M	.632
6481.878	3	3	*b*	D′–J	.878
6518.376	2	3	*b*	c–P	.375
6569.231	1	5	*d*	....	....
6575.022	2	3	*b*	c–M	.024
6593.878	2	3	*b*	v–L	.876
6609.116	2	4	*b*	c–M	.117
6663.444	2	4	*b*	....	.447
6705.117	1	3	....	....	....
6750.152	2	4	*b*	....	.157
6828.610	1	3	....	O–T′	.612
6841.349	1	4	....	O–T′	.355
6843.671	1	4	....	N–T′	.676
6855.176	1	4	....	O–T′	.179
6916.702	1	3	*d*	J–f	.709
6945.208	2	4	....	....	.211
6951.261	2	3	....	....	.271
6978.855	3	3	....	....	.857
6988.530	1	2	....	....	.531
6999.902	2	3	*d*	J–U	.912
7038.251	1	3	*d*	J–U	.255
7068.415	2	3	....	....	.418
7090.404	2	3	*d*	J–U	.410
7095.425	1	2	*d*	K′–U	....
7107.461	1	1	....	....	.464

TABLE VI—*Continued*

λ	No. Plates	Intensity	Group	Multiplet	Meggers and Kiess
7112.176	1	1	....	....	.178
7130.942	4	4	*d*	J–U	.946
7132.989	1	2	....	....	.996
7164.463	3	4	*d*	J–U	.472
7187.332	1	5	*d*	J–U	.341
7219.686	1	2	....	....	.690
7223.668	1	2	....	....	.670
7239.885	2	2	*d*	K′–U	.896
7288.760	1	3	*d*	K–U	.764
7293.068	1	3	*d*	K–U	.073
7311.101	1	2	*d*	K–U	.103
7389.414	4	4	*d*	K–U	.423
7411.174	4	3	*d*	K–U	.184
7445.769	3	3	*d*	K–U	.778
7495.084	4	3	*d*	K–U	.092
7511.042	4	4	*d*	K–U	.047
7531.162	1	2	*d*	L–f	.178
7586.048	1	3	*d*	L–f	.050

earlier ones, some supplementary results for the deep red are given in Table VI. These wave-lengths were obtained in terms of the neon standards, but from a Pfund arc shorter than the new international arc, and therefore presumably exhibit pole effect in some degree. They are given here because low intensity makes the measurement of such lines in the specified arc very difficult, and because the results are of some value for comparison with those of other observers. The last column of the table contains the wave-length found by Meggers and Kiess[1] in a 6-mm, 6-amp arc; the intensities are from their paper. The group designation for some of the lines has been deduced from unpublished observations which permit a reliable calculation of the pressure effect for many multiplets of iron.

For the lines marked *a* or *b* in Table VI there is no systematic difference between the wave-lengths in the first and last columns. For the *d* lines my results are systematically less than those of Meggers and Kiess, the mean difference being 0.007 A. For unclassified lines, some of which are known from other observations to belong to the stable groups, the difference is intermediate. Such a com-

[1] *Scientific Papers of the Bureau of Standards*, **19**, 273 (No. 479), 1924.

parison illustrates the difference in the arcs from which the two lists of wave-lengths were obtained. If the arc which I used had conformed to the specifications adopted for producing secondary standards, the differences noted above would have been greater. This table emphasizes the unfortunate fact that most of the stronger infra-red iron lines are unsuitable for use as standards of wave-length.

To Mrs. Thome, neé Keener, who measured a few of the photographs discussed in this paper, and to Mr. W. P. Hoge, who carried out nearly all the reductions as well as a large part of the measurement, my hearty thanks are extended. I am also indebted to Professor Russell and Miss Moore for access to unpublished data on the classification of iron lines.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
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THE ARC AND SPARK SPECTRA OF TITANIUM[1]

PART I. THE SPARK SPECTRUM, *Ti* II

By HENRY NORRIS RUSSELL[2]

ABSTRACT FOR PART I

A detailed analysis of the titanium spectrum aided by much unpublished material generously supplied by colleagues has led to the classification of practically all the lines except the weakest.

The *spark spectrum* includes *doublet* and *quartet* terms; 33 doublet and 17 quartet terms have been identified. Their combinations give 164 multiplets, including 529 observed lines. The *lowest energy-level* belongs to a $^4F'$ term. A second $^4F'$ term is 0.1 volt higher and a $^2F'$ term 0.5 volt above this.

Tables of the terms are given and also of the classified lines, including the few lines of any strength which remain unclassified.

The *temperature classification* of the lines shows the usual close relation to their levels of origin.

The *Zeeman effect* is in good agreement with Landé's theory. *Tables* of the observed and computed patterns are given.

The *electronic configurations* in the atom which give rise to the various terms have been identified with the aid of Hund's theory. The *agreement* of theory and observation is *complete*. The *complexity* of the spectrum is explained by the numerous possible spatial orientations of the orbits of the three spectroscopically active electrons.

Three *series* of two members each have been identified. They indicate an *ionization potential of* 13.6 *volts*.

Comparison of the spectra of *Ti* II and *Sc* I shows that Moseley's law is closely satisfied and confirms the theoretical interpretation of both.

I. INTRODUCTION

The spectrum of titanium is typical of those of the heavier elements as regards its apparent complexity—the lines are very numerous in both the arc and spark spectra, and no conspicuous series exist.

The first analysis of the arc spectrum was published by Dr. and Mrs. Kiess,[3] who classified about four hundred lines in multiplets belonging to triplet and quintet systems and indicated the probable existence of a singlet system. Shortly afterward Frl. Gieseler and

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 344.

[2] Research associate of the Mount Wilson Observatory, Carnegie Institution of Washington.

[3] C. C. and H. H. Kiess, *Proceedings of the Washington Academy of Sciences*, **13**, 270, 1923; *Journal of the Optical Society of America*, **8**, 607, 1924.

Dr. Grotrian[1] published an account of independent investigations, which in general confirmed the results of the authors first named, and showed by absorption observations that the normal state of the atom corresponds to a ^3F term.

The work of the present writer was begun at about the same time as that of the other investigators, without knowledge of the work of either. When it was learned later that Dr. and Mrs. Kiess were also in the field, publication was deliberately delayed until after their results were presented and attention was given to making the present analysis as complete as possible.

A similar analysis of the spark spectrum, begun a little later, has likewise been carried approximately to completion. The only previous investigation known to the writer is a brief note by N. K. Sur.[2] Still later the analysis has been extended to higher degrees of ionization, *Ti* III and *Ti* IV. This has been a long task—particularly since experience has shown that the best road to success in the analysis of a complicated spectrum is to drop the work when no further immediate results are forthcoming and to take it up again after a month or two, when new terms have almost always been found. It is probable that, even now, more remains that could be unraveled, but since all the lines of any strength have been classified (except a few in the extreme ultra-violet), the two main purposes of the investigation have been met. These were to provide the data necessary for the astrophysical interpretation of the behavior of titanium lines in the spectra of the sun and stars and to determine how completely the methods of multiplet analysis on the principles introduced by Sommerfeld and Landé are able to account for these rich and complex spectra. During the progress of the work, the theory of spectral structure has been developed by Heisenberg, Pauli, and Hund, and may be applied to the results of the term analysis.

It may be said at once that the confirmation of theory by observation is extremely satisfactory. Practically all the titanium lines of any importance have been referred to transitions between definite energy-levels in the atom in one or the other of its states of ionization; these levels may be grouped into multiple terms satisfying the

[1] *Zeitschrift für Physik*, **25**, 342, 1924.

[2] *Nature*, **114**, 611, 1924.

well-known rules; and Hund's theory gives a satisfactory account of the origin of these terms in electron configurations within the atom.

A few of the multiplets found in the writer's work upon *Ti* II have been published in detail,[1] and a summary account of the classification of 317 lines of *Ti* I and 121 of *Ti* II (including all the stronger ones with wave-lengths exceeding 3000 A) is found in his "List of Ultimate and Penultimate Lines."[2]

The analysis of *Ti* III and *Ti* IV has recently been published by the writer and Professor R. J. Lang.[3] The present communication, which gives full details for *Ti* I and *Ti* II, completes the presentation.

2. THE OBSERVATIONS

The observations of the arc and spark spectra upon which the present work is based have been derived from many sources. The main reliance for the wave-lengths was originally upon Kilby's[4] measures, extended toward the red by those of Kiess and Meggers[5] and supplemented as regards the fainter lines by the invaluable tables of Exner and Haschek.[6] The later precise measures of Crew[7] have also been utilized, and additional lines have been taken from observations of R. J. Lang[8] and other observers. The intensities and temperature classes determined by King[9] have been of fundamental importance in the analysis, as has also the observed behavior of the lines in the sun-spot spectrum. King's observations of the Zeeman effect[10] have also been freely employed.

In addition to these published data, much valuable material

[1] Meggers, Kiess, and Walters, *Journal of the Optical Society of America*, **9**, 363–364, 1924.

[2] *Mt. Wilson Contr.*, No. 286; *Astrophysical Journal*, **61**, 247–257, 1925.

[3] *Mt. Wilson Contr.*, No. 337; *Astrophysical Journal*, **66**, 13, 1927.

[4] *Astrophysical Journal*, **30**, 243, 1909.

[5] *Scientific Papers of the Bureau of Standards*, **16**, 54 (No. 372), 1920.

[6] Kayser, *Handbuch der Spectroscopie*, **6**, 655, 1912.

[7] *Astrophysical Journal*, **60**, 108, 1924.

[8] Private communication.

[9] *Mt. Wilson Contr.*, No. 76; *Astrophysical Journal*, **39**, 139, 1914; *Mt. Wilson Contr.*, No. 274; *Astrophysical Journal*, **59**, 155, 1924.

[10] *Publications of the Carnegie Institution of Washington*, No. 153, 35, 1912.

has been derived from unpublished sources. Measures of additional lines in the infra-red and ultra-violet made at the Bureau of Standards have been generously communicated by Dr. Kiess; and a plate of the spark spectrum in the extreme ultra-violet was taken for the writer by Professor Shenstone at Princeton with a large quartz spectrograph. The most valuable aid of all came from the writer's colleagues at this observatory.

A series of contact prints and enlargements of the furnace, arc, and spark spectra of the metal, prepared for the writer by Mr. A. S. King, and covering the whole range from λ 8800 to λ 2150, have proved of very great aid throughout the work; and many new lines have been measured upon these, or upon King's original negatives. Unpublished measures of the Zeeman effect made by Mr. Babcock for the purpose have also been of much service.

Hearty acknowledgments are made to all those mentioned above for their generous aid; and likewise to Miss Charlotte E. Moore for very valuable help in preparing the material for publication.

3. STRUCTURE OF THE SPARK SPECTRUM, *Ti* II—LIST OF TERMS

It is of advantage to discuss the spark spectrum first, both because it is simpler, and because a knowledge of it is necessary in interpreting certain features of the arc spectrum.

The most conspicuous spectral feature of the titanium spark is a great mass of strong lines in the near ultra-violet. Enhanced lines appear also in the visible region, though there are very few in the yellow and red. These are but faintly present in the arc, but many of the ultra-violet lines are strong lines there, and some appear in the furnace, even at moderate temperatures, and so fall into King's class III. These lines are numerous between λ 3000 and λ 3400. A pair at λλ 3759, 3761 and an isolated line at λ 3685 are also noteworthy. One line at λ 3349.41 is placed in class II and is the strongest *raie ultime* of the ionized atom. These persistent lines are heavily reversed in the spark, some symmetrically, while others are widened toward the red. The strongest of these are very conspicuous in the flash spectrum and rise to great heights in the chromosphere and even in the prominences.

On beginning the analysis it was found that the strongest sym-

metrically reversed lines, including the *raies ultimes*, belong to multiplets arising from transitions from a $^4F'$ term to a triad of D′, F, and G′ terms of the quartet system. A second $^4F'$ term, less than 1000 units higher, combines with the same triad, giving those lines which are unsymmetrically reversed in the spark. Two $^4P'$ terms close together were found later, which combine with the $^4D'$ term already mentioned to give multiplets in the violet, and with a new triad $^4S'$ ^4P $^4D'$, giving strong groups in the region λ 3100–λ 3300.

Numerous doublet terms are also present. A start in analyzing these was obtained by the Zeeman effect, which led to the identification of skew-symmetrical groups of types DD′, etc. It soon appeared that there is an important term with frequency separation 269.0, but the various combinations appeared to be inconsistent, some indicating that this was an F and others that it was a D term. The puzzle was solved by the recognition that there are two doublet terms with just this separation. The $^2F'$ term is the lowest in the doublet system and combines with a higher ^2F term to give the strong lines at λλ 3759, 3761. Its combination with the $^2D'$ term of identical separation (whose relative value was fixed by other combinations) led exactly to the very strong isolated line at λ 3685, which was thus found not to be a singlet, which would have no excuse for existence in a spectrum of even multiplicity, but an unresolvably close pair. The separation of this pair as calculated from the known separations of the terms involved can hardly exceed 0.002 A, and may be much less.

Many other doublet terms of all types from ^2S to ^2H were found, the combinations between these accounting for most of the outstanding strong lines. Numerous intercombinations between the doublet and quartet systems were also detected, and served to prove that the two $^4F'$ terms are the lowest in the whole scheme, and the $^2F'$ term the next.

A great many strong lines remaining in the region λ 3000–λ 2600 are hazy, but not reversed, in the spark, and appear faintly, if at all, in the arc. The most conspicuous of these were identified as combinations between the terms of the triad $^4D'$, ^4F, $^4G'$ and still higher terms of types ^4D, $^4F'$, ^4G, $^4H'$; and most of the rest, as similar combinations in the doublet system. Finally, several very high-

TABLE I

Ti II, Terms and Combinations

Type	Term	Combinations				
a^2S_1...	21338.00	a^2S'	a^2P	c^2P	a^4P	
		3	4	98	13	
$a^2P'_2$...	9975.92	a^2S'	a^2P	b^2P	a^2D'	b^2D'
	125.02	52	70	129	19	66
$a^2P'_1$...	9850.90	c^2D'	a^2F	b^2F	c^2F	a^4P
		124	17	75	140	101
		a^4D'	b^4D'			
		29	84			
$b^2P'_2$...	16625.25	a^2S'	a^2P	b^2P	c^2P	a^2D'
	109.46	14	33	64	136	2
$b^2P'_1$...	16515.79	b^2D'	c^2D'	d^2D'		
		31	58	139		
a^2D_3...	8744.27	a^2S'	a^2P	b^2P	a^2D'	b^2D'
	33.80	63	87	138	34	82
a^2D_2...	8710.47	c^2D'	d^2D'	a^2F	b^2F	c^2F
		135	157	28	92	143
		a^4S'	a^4P	b^4P	a^4D'	b^4D'
		94	112	161	37	99
		c^4D'	a^4F	a^4G'		
		154	25	15		
b^2D_3..	12758.15	a^2P	b^2P	a^2D'	b^2D'	c^2D'
	129.38	47	108	7	45	103
b^2D_2..	12628.77	d^2D'	a^2F	b^2F	c^2F	a^4D'
		152	5	50	122	10
		b^4D'				
		54				
c^2D_3...	25193.04	b^2P	c^2P	c^2D'	d^2D'	e^2D'
	231.70	11	56	9	59	156
c^2D_2...	24961.34	b^2F	c^2F	d^2F	e^2F	c^4D'
		1	26	118	158	49
$a^2F'_4$...	4897.60	a^2P	a^2D'	b^2D'	c^2D'	d^2D'
	268.99	125	48	120	150	163
$a^2F'_3$...	4628.61	a^2F	b^2F	a^2G'	b^2G'	a^4D'
		44	126	71	146	55
		b^4D'	c^4D'	a^4F	a^4G'	
		131	162	43	40	
$b^2F'_4$...	20891.88	b^2P	c^2D'	b^2F	c^2F	b^2G'
	−59.89	39	38	6	46	32
$b^2F'_3$...	20951.77					
$c^2F'_4$...	63444.76	a^2D'	a^2F	a^2G'		
	276.53	95	100	62		
$c^2F'_3$...	63168.23					
$d^2F'_4$...	65458.65	a^2D'	a^2F	a^4F		
	145.94	111	115	117		
$d^2F'_3$...	65312.71					

Type	Term	Combinations				
a^2G_5...	9118.15	a^2D'	b^2D'	a^2F	b^2F	a^2G'
	120.46	35	81	24	88	42
a^2G_4...	8997.69	b^2G'	a^2H	a^4F	a^4G'	
		121	137	23	12	
b^2G_5...	15257.53	b^2F	c^2F	d^2F	a^2G'	b^2G'
	−8.07	41	104	155	8	61
b^2G_4...	15265.60	a^2H				
		80				
c^2G_5...	67820.87	a^2F	a^2G'			
	216.67	132	110			
c^2G_4...	67604.20					
$a^2H'_6$...	12774.81	b^2F	a^2G'	b^2G'	a^2H	
	97.82	51	22	90	109	
$a^2H'_5$...	12676.99					
$b^2H'_6$..	68582.34	a^2G'				
	253.39	113				
$b^2H'_5$..	68328.95					
$a^4P'_3$...	9518.05	a^4S'	a^4P	b^4P	a^4D'	b^4D'
	122.29	83	107	160	36	93
$a^4P'_2$...	9395.76	a^4F	a^2S'	a^2P	b^2P	a^2D'
	32.05	18	57	78	134	27
$a^4P'_1$...	9363.71	b^2D'	c^2D'	a^2F		
		73	128	20		
$b^4P'_3$...	10024.74	a^4S'	a^4P	b^4P	a^4D'	b^4D'
	94.00	76	102	159	30	79
$b^4P'_2$...	9930.74	c^4D'	a^2S'	a^2P	a^2D'	b^2D'
	57.87	153	53	69	21	65
$b^4P'_1$...	9872.87	a^2F				
		16				
a^4D_4...	66996.67	a^4F				
	58.97	130				
a^4D_3...	66937.70					
	121.21					
a^4D_2...	66816.49					
	49.06					
a^4D_1...	66767.43?					
$a^4F'_5$...	393.22	a^4D'	b^4D'	c^4D'	a^4F	a^4G'
	167.75	106	151	164	85	68
$a^4F'_4$...	225.47	a^2D'	b^2D'	a^2F	b^2F	a^2G'
	131.53	97	147	89	149	119
$a^4F'_3$...	93.94					
	93.94					
$a^4F'_2$...	0.00					

TABLE I—*Continued*

Type	Term	Combinations				
$b^4F'_5$...	1215.58	a^4D'	b^4D'	a^4F	a^4G'	a^2D'
	128.37	96	148	74	60	86
$b^4F'_4$...	1087.21	b^2D'	a^2F	b^2F		
	103.41	142	77	144		
$b^4F'_3$...	983.80					
	75.84					
$b^4F'_2$...	907.96					
$c^4F'_5$...	62594.27	a^4D'	a^4F	a^4G'		
	184.69	72	91	105		
$c^4F'_4$...	62409.58					
	138.33					
$c^4F'_3$...	62271.25					
	91.23					
$c^4F'_2$...	62180.02					
$d^4F'_5$...	69081.35	a^4D'	b^4D'	a^4F	a^4G'	
	130.96	133	67	141	145	
$d^4F'_4$...	68950.39					
	105.25					
$d^4F'_3$...	68845.14					
	77.48					
$d^4F'_2$...	68767.66					
a^4G_6...	65241.60	a^4F	a^4G'			
	147.31	114	123			
a^4G_5...	65094.29					
	116.72					
a^4G_4...	64977.57					
	92.92					
a^4G_3...	64884.65					
$a^4H'_7$...	65589.10	a^4F	a^4G'			
	143.25	116	127			
$a^4H'_6$...	65445.85					
	138.40					
$a^4H'_5$...	65307.45					
	122.73					
$a^4H'_4$...	65184.72					
$a^2S'_1$...	37430.55	a^2S	a^2P'	b^2P'	a^2D	a^4P'
		3	52	14	63	57
		b^4P'				
		53				
a^2P_2...	39602.90	a^2S	a^2P'	b^2P'	a^2D	b^2D
	−71.74	4	70	33	87	47
a^2P_1...	39674.64	a^2F'	a^4P'	b^4P'		
		125	78	69		
b^2P_2...	45548.90	a^2P'	b^2P'	a^2D	b^2D	c^2D
	76.01	129	64	138	108	11
b^2P_1...	45472.89	b^2F'	a^4P'			
		39	134			

Type	Term	Combinations				
c^2P_2...	53128.17	a^2S	b^2P'	c^2D		
	6.69	98	136	56		
c^2P_1...	53121.48					
$a^2D'_3$...	32025.50	a^2P'	b^2P'	a^2D	b^2D	a^2F'
	269.00	19	2	34	7	48
$a^2D'_2$...	31756.50	c^2F'	d^2F'	a^2G	a^4P'	b^4P'
		95	111	35	27	21
		a^4F'	b^4F'			
		97	86			
$b^2D'_3$...	39476.87	a^2P'	b^2P'	a^2D	b^2D	a^2F'
	243.43	66	31	82	45	120
$b^2D'_2$...	39233.44	a^2G	a^4P'	b^4P'	a^4F'	b^4F'
		81	73	65	147	142
$c^2D'_3$...	44902.42	a^2P'	b^2P'	a^2D	b^2D	c^2D
	−12.38	124	58	135	103	9
$c^2D'_2$...	44914.80	a^2F'	b^2F'	a^4P'		
		150	38	128		
$d^2D'_3$...	53554.90	b^2P'	a^2D	b^2D	c^2D	a^2F'
	−41.80	139	157	152	59	163
$d^2D'_2$...	53596.70					
$e^2D'_3$..	69622.15	c^2D				
	294.83	156				
$e^2D'_2$...	69327.32					
a^2F_4...	31490.82	a^2P'	a^2D	b^2D	a^2F'	c^2F'
	283.38	17	28	5	44	100
a^2F_3...	31207.44	d^2F'	a^2G	c^2G	a^4P'	b^4P'
		115	24	132	20	16
		a^4F'	b^4F'			
		89	77			
b^2F_4...	40074.71	a^2P'	a^2D	b^2D	c^2D	a^2F'
	147.88	75	92	50	1	126
b^2F_3...	39926.83	b^2F'	a^2G	b^2G	a^2H'	a^4F'
		6	88	41	51	149
		b^4F'				
		144				
c^2F_4...	47466.80	a^2P'	a^2D	b^2D	c^2D	b^2F'
	−158.37	140	143	122	26	46
c^2F_3...	47625.17	b^2G				
		104				
d^2F_4...	59467.81	c^2D	b^2G			
	146.02	118	155			
d^2F_3...	59321.79					
e^2F_4...	70893.00	c^2D				
	286.65	158				
e^2F_3...	70606.35					

TABLE I—*Continued*

Type	Term	Combinations				
$a^2G'_5$...	34748.50	a^2F'	c^2F'	a^2G	b^2G	c^2G
	205.14	71	62	42	8	110
$a^2G'_4$...	34543.36	a^2H'	b^2H'	a^4F'		
		22	113	119		
$b^2G'_5$...	43780.99	a^2F'	b^2F'	a^2G	b^2G	a^2H'
	40.22	146	32	121	61	90
$b^2G'_4$...	43740.77					
a^2H_6...	45908.56	a^2G	b^2G	a^2H'		
	234.81	137	80	109		
a^2H_5...	45673.75					
$a^4S'_2$...	40027.28	a^4P'	b^4P'	a^2D		
		83	76	94		
a^4P_3...	42208.84	a^4P'	b^4P'	a^2S	a^2P'	a^2D
	139.99	107	102	13	101	112
a^4P_2...	42068.85					
	72.11					
a^4P_1...	41996.74					
b^4P_3...	56325.94	a^4P'	b^4P'	a^2D		
	76.83	160	159	161		
b^4P_2...	56249.11					
	25.98					
b^4P_1...	56223.13					
$a^4D'_4$...	32767.02	a^4P'	b^4P'	a^4F'	b^4F'	c^4F'
	69.08	36	30	106	96	72
$a^4D'_3$...	32697.94	d^4F'	a^2P'	a^2D	b^2D	a^2F'
	95.43	133	29	37	10	55
$a^4D'_2$...	32602.51					
	70.13					
$a^4D'_1$...	32532.38					
$b^4D'_4$...	40798.37	a^4P'	b^4P'	a^4F'	b^4F'	d^4F'
	216.57	93	79	151	148	67
$b^4D'_3$...	40581.80	a^2P'	a^2D	b^2D	a^2F'	
	156.00	84	99	54	131	
$b^4D'_2$...	40425.80					
	95.55					
$b^4D'_1$...	40330.25					
$c^4D'_4$...	52631.07	b^4P'	a^4F'	a^2D	c^2D	a^2F'
	159.59	153	164	154	49	162
$c^4D'_3$...	52471.48					
	12.50					
$c^4D'_2$...	52458.98					
	129.20					
$c^4D'_1$...	52329.78					
a^4F_5...	31300.92	a^4P'	a^4D	a^4F'	b^4F'	c^4F'
	187.31	18	130	85	74	91
a^4F_4...	31113.61	d^4F'	a^4G	a^4H'	a^2D	a^2F'
	154.91	141	114	116	25	43
a^4F_3...	30958.70	d^2F'	a^2G			
	122.18	117	23			
a^4F_2...	30836.52					
$a^4G'_6$...	30240.68	a^4F'	b^4F'	c^4F'	d^4F'	a^4G
	272.60	68	60	105	145	123
$a^4G'_5$...	29968.08	a^4H'	a^2D	a^2F'	a^2G	
	233.63	127	15	40	12	
$a^4G'_4$...	29734.45					
	190.08					
$a^4G'_3$...	29544.37					

lying terms were discovered, which combine with the low terms first mentioned to give multiplets occurring between λ 2450 and λ 1906, the shortest wave-length observed.

In all, 33 doublet terms and 17 quartet terms have been identified. They are listed in Table I. The term values are counted upward from the lowest energy-level, $a^4F'_2$, those of all the other terms being fixed by various combinations. The letters "a," "b," "c," are used simply to label the various terms of the same type and have no theoretical significance.

The combinations which have been observed between these terms are listed in Table I. They give rise in all to 87 multiplets belonging to the doublet system, 33 of the quartet system, and 44 inter-

combinations—164 in all. To facilitate reference, the numbers which have been assigned to the multiplets in Table II are inserted below the combinations in Table I; thus the combination a^2S-a^2S' gives multiplet number 3. It may be remarked that no less than 14 of these multiplets involve combinations between terms which differ by two units in the apparent azimuthal quantum number (Hund's L)—for example, a^2G-b^2D'. Such transitions are quite possible in the more complex spectra, but usually give faint lines. Figures 1 and 2 represent the relations of these terms. Owing to the complexity of the spectrum, the doublet and quartet terms are shown in separate diagrams. Those doublet terms, however, which combine with higher-lying quartet terms, are plotted on the quartet diagram, and vice versa, and the observed intercombinations are indicated by dotted lines.

4. TABLE OF LINES OF *Ti* II

To give all these multiplets in the conventional form would occupy far too much space, and it may suffice to list all the lines of *Ti* II in order of wave-length, and give the designations for those which have been classified. This is done in Table II. The first column indicates the source from which the wave-length is taken, the notation being explained at the end of the table; the second, the observed wave-length; and the third, the excess of this, in hundredths of an angstrom, above that computed from the term values of Table I. In the fourth and fifth columns are found the intensities of the lines in the arc and the condensed spark. As the previous data were very far from homogeneous, the intensities in the spark have been estimated anew on a uniform scale, upon original plates and enlargements of the spectrum of the condensed spark. Estimates of selected lines of all degrees of intensity, sufficient to fix the scale, were made by Mr. King, and, with these as standards, the remainder were observed by Miss Moore. These estimates represent the observable photographic intensity, and the values therefore tend to be low for the long and short wave-lengths. Lines barely visible on the plates are denoted by "tr." For lines which could not be seen there at all, the estimates of Exner and Haschek or, when necessary, of other observers, are entered in parentheses. The lines

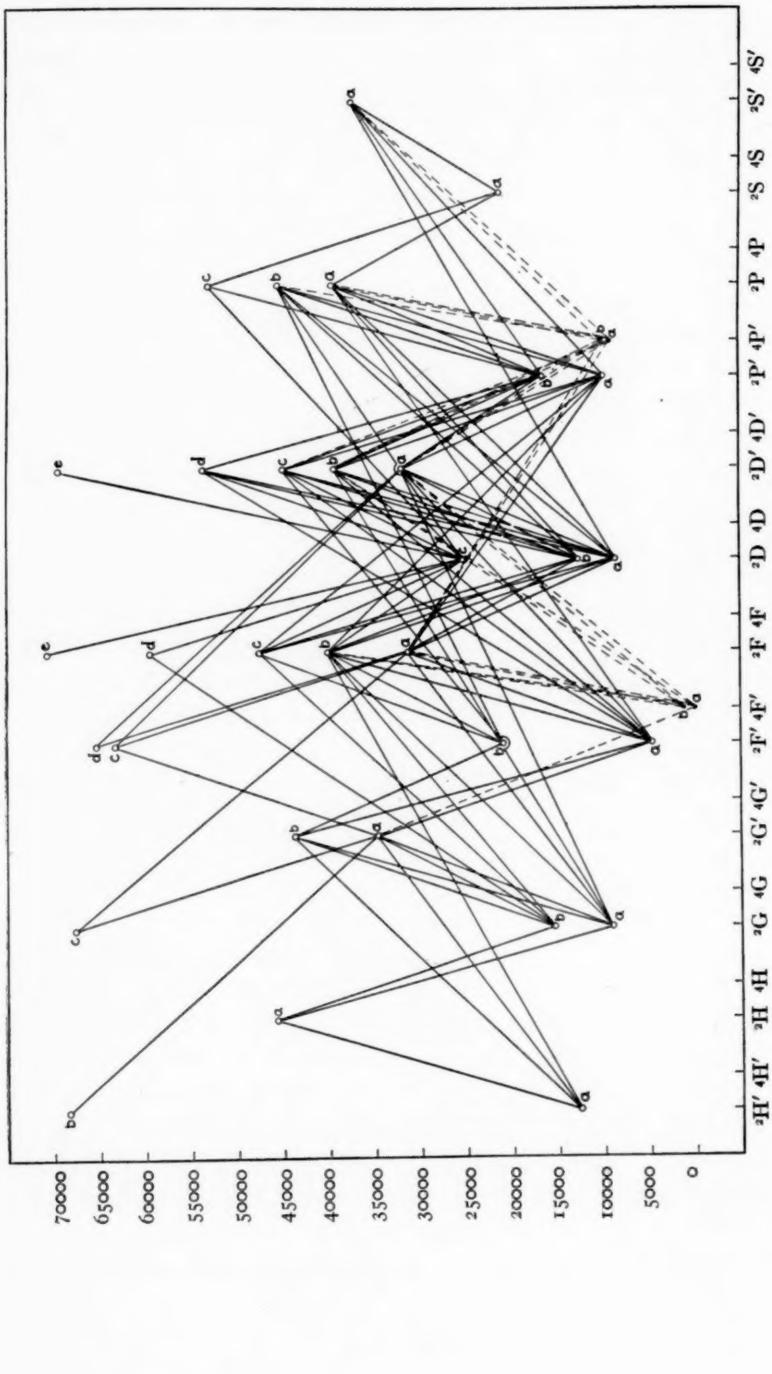

FIG. 1.—*Ti* II doublet combinations

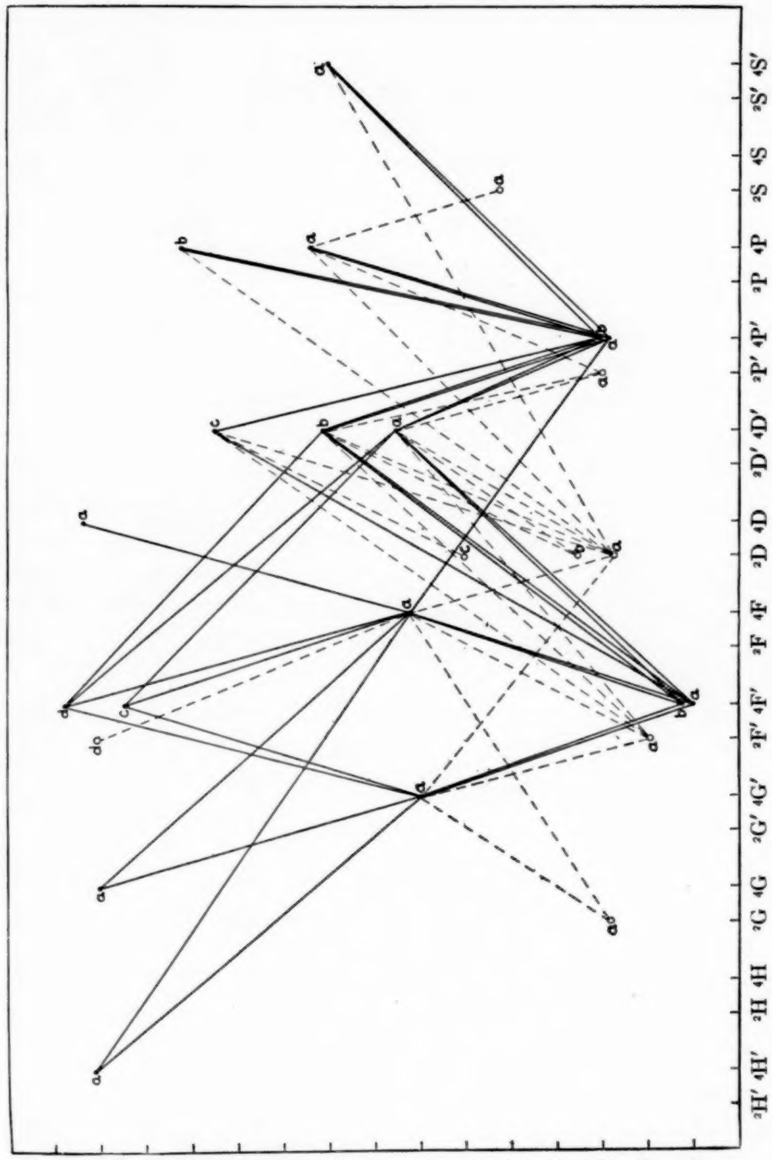

FIG. 2.—*Ti* II quartet combinations

for which the intensity is thus bracketed are faint, except for wave-lengths less than 2400 A, for which the concave grating is at a disadvantage. The sixth column gives King's temperature classification, when available. The letter "r" denotes a line which is reversed in the spectrum of the condensed spark while "u" is added if the reversal is unsymmetrical. The seventh column contains the wave number *in vacuo*, ν, and the eighth, the identification of those lines which have been classified.

To facilitate identification of the various multiplets, the last column has been added. In this the multiplets are numbered in order of their position in the spectrum—that containing the first line on the list is numbered 1, and all other lines in this multiplet receive the same number, and so on.

All lines which are known to belong to the spectrum of *Ti* II and are of intensity greater than 3 on the scale here adopted, or 2 on Exner and Haschek's scale, are included in the table, and also all the fainter lines which have been classified. The unclassified lines are recognizable by the blanks in the last two columns. They number 31, and the strongest is of intensity 30, while the classified lines number 529, and run up to intensity 250.

There are many other faint unclassified lines which have been attributed to *Ti* II and in many cases probably belong to this spectrum. They may be found in tables in Kayser's *Handbuch*.

5. TEMPERATURE CLASSIFICATION

The relation between the temperature class and the level of origin is fully as conspicuous for enhanced lines as for the arc lines. This is very well illustrated by Table II.

Beginning with the lowest energy-level, a^4F', all the stronger lines which originate (in absorption) in this level are of temperature class IIIr (heavily reversed in the spark) and appear in the furnace at a temperature of about 2250°,[1] while the strongest line of all appears at 2000° and is of class II. Even the weakest lines in these multiplets, and many of the intersystem combinations originating in this level, appear in the furnace at 2600°, and are placed in class IV.

[1] A. S. King, *Mt. Wilson Contr.*, No. 274; *Astrophysical Journal*, **59**, 155, 1924.

TABLE II

Ti II, Identified Lines

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multiplet
4	6717.89	+7	......	(1u)	......	14881.52	$c^2D_3-b^2F_4$	1
2	6680.26	+6	......	(1)	......	14965.36	$c^2D_2-b^2F_3$	1
3	6559.58	+1	......	(1)	......	15240.68	$b^2P'_1-a^2D'_2$	2
3	6491.68	+7	......	(2)	......	15400.08	$b^2P'_2-a^2D'_3$	2
3	6212.29	−3	......	(1)	......	16092.68	$a^2S_1-a^2S'_1$	3
1	5473.52	+6	......	(1)	......	18264.73	$a^2S_1-a^2P_2$	4
3	5452.02	−3	......	(1)	......	18336.74	$a^2S_1-a^2P_1$	4
11	5418.77	+1	1	0	V	18449.26	$b^2D_3-a^2F_3$	5
3	5381.02	−1	......	1	......	18578.69	$b^2D_2-a^2F_3$	5
11	5336.78	−1	2	4	V	18732.70	$b^2D_3-a^2F_4$	5
3	5268.63	+1	......	1	......	18975.01	$b^2F'_3-b^2F_3$	6
3	5262.14	−2	......	0	......	18998.41	$b^2D_3-a^2D'_2$	7
6	5226.56	0	3	5	V	19127.73	$b^2D_2-a^2D'_2$	7
3	5211.58	+3	......	0	......	19182.72	$b^2F'_4-b^2F_4$	6
6	5188.70	+1	4	6	V	19267.30	$b^2D_3-a^2D'_3$	7
11	5185.90	+2	......	2	......	19277.70	$b^2G_4-a^2G'_4$	8
3	5183.73	+1	......	tr	......	19285.78	$b^2G_5-a^2G'_4$	8
11	5154.07	−1	......	0	......	19396.76	$b^2D_2-a^2D'_3$	7
11	5129.17	+1	......	1	......	19490.92	$b^2G_5-a^2G'_5$	8
11	5072.30	−2	......	2	......	19709.44	$c^2D_3-c^2D'_3$	9
3	5069.12	−1	......	tr	......	19721.81	$c^2D_3-c^2D'_2$	9
11	5013.69	−2	......	tr	......	19939.85	$b^2D_3-a^4D'_3$	10
3	5010.21	−6	......	tr	......	19953.70	$c^2D_2-c^2D'_2$	9
6	4911.19	−3	......	0	......	20356.00	$c^2D_3-b^2P_2$	11
3	4873.95	+1	......	tr	......	20511.53	$c^2D_2-b^2P_1$	11
3	4865.62	+1	......	tr	......	20546.64	$a^2G_4-a^4G'_3$	12
3	4839.22	0	......	(1)	......	20658.74	$a^2S_1-a^4P_1$	13
6	4805.11	−2	4	2	V	20805.38	$b^2P'_2-a^2S'_1$	14
3	4798.52	−1	......	(2)	......	20833.96	$a^2D_2-a^4G'_3$	15
3	4779.99	+1	2	1	V	20914.71	$b^2P'_1-a^2S'_1$	14
3	4762.78	−2	......	(1)	......	20990.29	$a^2D_3-a^4G'_4$	15
3	4719.51	−1	......	(1)	......	21182.74	$b^4P'_3-a^2F_3$	16
3	4708.65	−2	......	tr	......	21231.59	$a^2P'_2-a^2F_3$	17
11	4657.20	−1	......	tr	......	21466.14	$b^4P'_3-a^2F_4$	16
3	4636.34	+5	......	(1)	......	21562.72	$a^4P'_2-a^4F_3$	18
6	4589.96	0	3	2	V	21780.60	$a^2P'_2-a^2D'_2$	19
3	4583.44	+2	......	(1)	......	21811.59	$a^4P'_2-a^2F_3$	20
3	4580.46	0	......	(1)	......	21825.78	$b^4P'_2-a^2D'_2$	21
6	4571.98	+2	15	50n	V	21866.26	$a^2H'_5-a^2G'_4$	22
3	4568.30	−5	......	(1)	......	21883.87	$b^4P'_1-a^2D'_2$	21
6	4563.77	0	15	30	V	21905.60	$a^2P'_1-a^2D'_2$	19
6	4549.64	+1	25	60n	V	21973.64	$a^2H'_6-a^2G'_5$	22
3	4545.14	+2	......	tr	......	21995.38	$a^2G_5-a^4F_4$	23
3	4544.01	−2	......	tr	......	22000.85	$b^4P'_3-a^2D'_3$	21
6	4533.97	0	20	30	V	22049.57	$a^2P'_2-a^2D'_3$	19
3	4529.46	−1	1	1	V	22071.54	$a^2H'_5-a^2G'_5$	22
3	4524.72	+2	......	(1?)	......	22094.65	$b^4P'_2-a^2D'_3$	21
6	4501.27	0	25	40	V	22209.75	$a^2G_4-a^2F_3$	24
3	4493.52	+4	......	(1)	......	22248.05	$a^2D_2-a^4F_3$	25
6	4488.32	−2	2	15	V	22273.84	$c^2D_3-c^2F_4$	26
6	4470.88	+1	2	tr	IV	22360.71	$a^4P'_2-a^2D'_2$	27
11	4469.15	−1	1	tr	V	22369.37	$a^2D_3-a^4F_4$	25

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multiplet
6	4468.49	0	25	50	V	22372.67	$a^2G_5-a^2F_4$	24
6	4464.47	−1	2	1	V	22392.82	$a^4P'_1-a^2D'_2$	27
3	4456.62	−3	......	tr	......	22432.26	$c^2D_3-c^2F_3$	26
6	4450.49	0	4	10	V	22463.15	$a^2D_3-a^2F_3$	28
6‡	4444.56	0	1	1	V	22493.13	$a^2G_4-a^2F_4$	24
6	4443.80	0	25	50	V	22496.97	$a^2D_2-a^2F_3$	28
3	4432.1	+2	......	tr	......	22556.36	$a^2P'_2-a^4D'_1$	29
3	4421.95	+1	......	1	......	22608.14	$b^2P'_2-b^2D'_2$	31
11	4418.33	−1	1	1	V	22626.65	$a^2P'_2-a^4D'_2$	29
6	4417.71	+2	8	40	V	22629.84	$a^4P'_2-a^2D'_3$	27
3	4411.94	+2	......	(1)	......	22659.43	$b^4P'_1-a^4D'_1$	30
3	4411.10	+2	......	15	......	22663.75	$c^2D_2-c^2F_3$	26
3	4409.53	−1	......	tr	......	22671.82	$b^4P'_2-a^4D'_2$	30
5	4409.23	−3	......	tr	......	22673.36	$b^4P'_3-a^4D'_3$	30
6	4407.68	+3	......	1	......	22681.32	$a^2P'_1-a^4D'_1$	29
6	4399.77	−2	6	35	V	22722.10	$a^2P'_2-a^4D'_3$	29
3	4398.31	0	......	(1)	......	22729.65	$b^4P'_1-a^4D'_2$	30
6	4395.86	0	1	2	V	22742.30	$b^4P'_3-a^4D'_4$	30
6	4395.04	0	25	60	V	22746.55	$a^2D_3-a^2F_4$	28
11	4394.06	0	2	2	V	22751.63	$a^2P'_1-a^4D'_2$	29
11	4391.02	−4	......	tr	......	22767.39	$b^4P'_2-a^4D'_3$	30
11	4386.84	−1	......	10	......	22789.07	$b^2F'_3-b^2G'_4$	32
3	4374.82	−1	......	1	......	22851.68	$b^2P'_2-b^2D'_3$	31
11	4367.67	0	1	15	V	22889.09	$b^2F'_4-b^2G'_5$	32
11	4350.83	−1	......	1	......	22977.68	$b^2P'_2-a^2P_2$	33
6	4344.31	+1	3	2	V	23012.17	$a^2D_3-a^2D'_2$	34
6	4341.39	+3	2	1	V	23027.65	$a^2G_4-a^2D'_3$	35
6	4337.92	−1	10	50	V	23046.06	$a^2D_2-a^2D'_2$	34
3	4337.32	+3	......	(1)	......	23049.25	$b^2P'_2-a^2P_1$	33
11	4330.71	0	1	0	V	23084.44	$a^4P'_3-a^4D'_2$	36
3	4330.25	+4	......	0	......	23086.89	$b^2P'_1-a^2P_2$	33
6	4320.95	+1	1	1	V	23136.58	$a^4P'_2-a^4D'_1$	36
11	4316.80	+1	......	1	......	23158.81	$b^2P'_1-a^2P_1$	33
11	4314.98	+1	5	40	V	23168.59	$a^4P'_1-a^4D'_1$	36
6	4312.88	+1	7	35	V	23179.86	$a^4P'_3-a^4D'_3$	36
6	4307.89	+1	12	40	V	23206.72	$a^4P'_2-a^4D'_2$	36
6	4301.93	−1	5	15	V	23238.87	$a^4P'_1-a^4D'_2$	36
6	4300.05	−1	12	60	V	23249.02	$a^4P'_3-a^4D'_4$	36
6	4294.10	0	8	40	V	23281.24	$a^2D_3-a^2D'_3$	34
6	4290.23	−1	8	50	V	23302.24	$a^4P'_2-a^4D'_3$	36
11	4287.88	0	2	2	V	23315.01	$a^2D_2-a^2D'_3$	34
3	4190.29	+4	......	(1)	......	23858.01	$a^2D_3-a^4D'_2$	37
3	4184.33	+1	......	0	......	23891.98	$a^2D_2-a^4D'_2$	37
3	4173.55	0	3	1	V	23953.69	$a^2D_3-a^4D'_3$	37
6	4171.91	−1	5	30	V	23963.11	$b^2F'_3-c^2D'_2$	38
6	4163.65	−2	8	40	V	24010.64	$b^2F'_4-c^2D'_3$	38
3	4161.54	−1	2	1	V	24022.81	$a^2D_3-a^4D'_4$	37
3	4064.40	+3	......	(1)	......	24596.96	$b^2F'_3-b^2P_2$	39
3	4056.20	+1	......	(1)	......	24646.68	$a^2F'_4-a^4G'_3$	40
6	4053.84	+3	4	3	V	24661.03	$b^2G_4-b^2F_3$	41
6	4028.35	+2	5	7	V	24817.07	$b^2G_5-b^2F_4$	41
6	4025.13	−1	4	2	V	24836.93	$a^2F'_4-a^4G'_4$	40
6	4012.40	+1	10	4	V	24915.72	$a^2F'_3-a^4G'_3$	40
3	3982.01	0	......	tr	......	25105.87	$a^2F'_3-a^4G'_4$	40

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multi-plet
6	3932.02	+2	......	2	....	25425.05	$a^2G_5-a^2G'_4$	42
6	3913.45	−1	18	60	V	25545.70	$a^2G_4-a^2G'_4$	42
6	3900.53	+1	20	70	V	25630.30	$a^2G_5-a^2G'_5$	42
6	3836.10	+5	1	1	V	26060.77	$a^2F'_4-a^4F_3$	43
3	3814.57	+1	......	4	....	26207.85	$a^2F'_3-a^4F_2$	43
6	3813.39	+1	2	2	IV?	26215.97	$a^2F'_4-a^4F_4$	43
3	3799.78	0	......	tr	....	26309.86	$a^2F'_4-a^2F_3$	44
3	3796.88	+2	......	2n	....	26329.96	$a^2F'_3-a^4F_3$	43
3	3776.04	0	......	6	....	26475.27	$b^2D_3-b^2D'_2$	45
3	3770.40	+2	......	(1)	....	26514.88	$b^2F'_3-c^2F_4$	46
3	3761.86	−2	......	15	....	26575.07	$b^2F'_4-c^2F_4$	46
6	3761.33	0	40	200	IVr	26578.81	$a^2F'_3-a^2F_3$	44
6	3759.30	+1	40	200	IVr	26593.16	$a^2F'_4-a^2F_4$	44
6	3757.68	0	8	30	V	26604.64	$b^2D_2-b^2D'_2$	45
1	3748.01	+2	......	10	....	26673.27	$b^2F'_3-c^2F_3$	46
3	3741.63	0	8	50	Vru	26718.74	$b^2D_3-b^2D'_3$	45
3	3739.5	−10	......	tr	....	26733.97	$b^2F'_4-c^2F_3$	46
11	3724.08	+1	......	1	....	26844.66	$b^2D_3-a^2P_2$	47
3	3723.60	0	......	tr	....	26848.11	$b^2D_2-b^2D'_3$	45
6	3721.64	−1	8	15	V	26862.26	$a^2F'_3-a^2F_4$	44
6	3706.22	+2	3	20	V	26974.02	$b^2D_2-a^2P_2$	47
3	3696.38	+1	......	(1)	....	27045.82	$b^2D_2-a^2P_1$	47
6*	3685.19	−1 −1	40	250	IVr	27127.94	$a^2F'_4-a^2D'_3$ $a^2F'_3-a^2D'_2$	48 48
9	3666.59	+5	......	(ou)	....	27265.56	$c^2D_3-c^4D'_2$	49
6	3662.22	0	4	40	V	27298.09	$b^2D_2-b^2F_3$	50
6	3659.75	+1	4	60	V	27316.50	$b^2D_3-b^2F_4$	50
9	3648.87	−3	......	(o)	....	27397.97	$a^2H'_5-b^2F_4$	51
6	3641.33	−1	10	100	V	27454.70	$a^2P'_2-a^2S'_1$	52
3	3627.70	−2	......	(1)	....	27557.84	$b^4P'_1-a^2S'_1$	53
6	3624.84	+1	8	70	V	27579.59	$a^2P'_1-a^2S'_1$	52
3	3596.55	+7	......	tr	....	27796.52	$b^2D_2-b^4D'_2$	54
6	3596.05	−1	10	60	V	27800.38	$a^2F'_4-a^4D'_3$	55
3	3593.11	+7	......	2	....	27823.13	$b^2D_3-b^4D'_3$	54
6	3587.13	−1	4	12	V	27869.51	$a^2F'_4-a^4D'_4$	55
9	3578.70	0	......	(o)	....	27935.16	$c^2D_3-c^2P_2$	56
9	3576.37	−4	......	(ou)	....	27953.35	$b^2D_2-b^4D'_3$	54
7	3573.72	−2	6	20	V	27974.08	$a^2F'_3-a^4D'_2$	55
3	3566.00	+2	2	6	V	28034.64	$a^4P'_2-a^2S'_1$	57
3	3565.33	+4	......	3	....	28039.91	$b^2D_3-b^4D'_4$	54
3	3561.92	+1	1	1	V	28066.76	$a^4P'_1-a^2S'_1$	57
3	3561.59	0	2	3	V	28069.36	$a^2F'_3-a^4D'_3$	55
6	3535.40	−1	10	40	V	28277.28	$b^2P'_2-c^2D'_3$	58
11	3533.85	−2	......	2	....	28289.69	$b^2P'_2-c^2D'_2$	58
3	3524.85	−1	......	tr	....	28361.92	$c^2D_3-d^2D'_3$	59
6	3520.25	0	8	20	V	28398.97	$b^2P'_1-c^2D'_2$	58
9	3513.08	+3	......	tr	....	28456.94	$b^4F'_4-a^4G'_3$	60
6	3510.84	+1	10	60	Vr	28475.09	$b^2G_4-b^2G'_4$	61
3	3509.85	+1	1	3	V	28483.13	$b^2G_5-b^2G'_4$	61
3	3505.91	+3	......	tr	....	28515.13	$b^2G_4-b^2G'_5$	61
6	3504.89	0	8	80	Vr	28523.43	$b^2G_5-b^2G'_5$	61
6	3500.33	0	4	2	IV	28560.59	$b^4F'_3-a^4G'_3$	60
3	3492.5	+3	......	3n	....	28624.62	$a^2G'_4-c^2F'_3$	62
6	3491.05	−1	8	10	IIIru	28636.51	$b^4F'_2-a^4G'_3$	60

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multi-plet
6.......	3489.74	0	4	2	IV	28647.26	$b^4F'_4-a^4G'_4$	60
3.......	3483.80	+2	......	4n	....	28696.09	$a^2G'_5-c^2F'_4$	62
6.......	3480.89	0	1	0	V	28720.09	$a^2D_2-a^2S'_1$	63
6.......	3477.18	−1	15	15	IIIru	28750.73	$b^4F'_3-a^4G'_4$	60
6.......	3476.99	+2	2	tr	V	28752.30	$b^4F'_5-a^4G'_5$	60
12.......	3465.58	+8	1	3	V	28846.97	$b^2P'_2-b^2P_1$	64
6.......	3461.50	−1	20	20	IIIru	28880.96	$b^4F'_4-a^4G'_5$	60
9.......	3459.01	−4	......	(0u)	....	28901.76	$a^2G'_4-c^2F'_4$	62
6.......	3456.40	+1	5	20	V	38923.58	$b^2P'_2-b^2P_2$	64
3.......	3452.42	+2	2	4	V	28956.92	$b^2P'_1-b^2P_1$	64
7.......	3444.31	0	15	30	IIIru	29025.10	$b^4F'_5-a^4G'_6$	60
3.......	3443.38	+2	......	1	....	29032.94	$b^2P'_1-b^2P_2$	64
3.......	3422.69	+3	......	(1)	....	29208.43	$b^4P'_3-b^2D'_2$	65
6.......	3416.95	0	3	2	IV	29257.50	$a^2P'_2-b^2D'_2$	66
9.......	3414.01	+3	......	(0)	....	29282.69	$b^4D'_4-d^4F'_5$	67
6.......	3409.80	+1	5	4	IV	29318.85	$a^4F'_4-a^4G'_3$	68
6.......	3407.20	0	4	3	IV	29341.23	$a^4F'_5-a^4G'_4$	68
3.......	3404.99	+3	......	(1)	....	29360.27	$b^4P'_1-b^2D'_2$	65
6.......	3402.42	+1	3	8	V	29382.44	$a^2P'_1-b^2D'_2$	66
6.......	3394.57	+1	15	40	IIIr	29450.38	$a^4F'_3-a^4G'_3$	68
6.......	3388.75	0	2	8	V	29500.97	$a^2P'_2-b^2D'_3$	66
6.......	3387.83	0	15	50	IIIr	29508.97	$a^4F'_4-a^4G'_4$	68
6.......	3383.76	−1	40	125	IIIr	29544.47	$a^4F'_2-a^4G'_3$	68
6.......	3380.28	0	15	30	IIIr	29574.88	$a^4F'_5-a^4G'_5$	68
11.......	3379.92	+1	......	1n	....	29578.03	$b^4P'_3-a^2P_2$	69
6.......	3374.34	0	2	8	V	29626.95	$a^2P'_2-a^2P_2$	70
6.......	3372.80	0	30	100	IIIr	29640.47	$a^4F'_3-a^4G'_4$	68
6.......	3372.20	0	5	10?	V	29645.74	$a^2F'_4-a^2G'_4$	71
12.......	3369.67	+8	......	0n	....	29668.00	$a^4D'_2-c^4F'_3$	72
6.......	3369.20	0	2	2	V	29672.14	$b^4P'_2-a^2P_2$	69
6†......	3366.17	−1	5	8	III	29698.84	$a^2P'_2-a^2P_1$	70
3.......	3364.86	+14	......	1n	....	29710.41	$a^4D'_3-c^4F'_4$	72
3.......	3362.66	+2	......	1	....	29729.85	$b^4P'_1-a^2P_2$	69
6.......	3361.22	0	40	125	IIIr	29742.58	$a^4F'_4-a^4G'_5$	68
6.......	3352.06	−1	1	5	V	29823.86	$a^2P'_1-a^2P_1$	70
3.......	3351.66	−2	......	1n	....	29827.42	$a^4D'_4-c^4F'_5$	72
7†......	3350.53	+2	......	1	....	29837.47	$a^4P'_2-b^2D'_2$	73
6.......	3349.41	0	40	125	IIr	29847.46	$a^4F'_5-a^4G'_6$	68
6.......	3349.02	0	20	75	IIIr	29850.93	$a^2F'_4-a^2G'_5$	71
6.......	3348.82	0	5	10?	III	29852.71	$b^4F'_3-a^4F_2$	74
6.......	3346.72	0	7	15	III	29871.45	$b^4F'_4-a^4F_3$	74
6.......	3343.76	+2	6	10	III	29897.88	$b^4F'_5-a^4F_4$	74
6†......	3341.87	0	50	100	IIr	29914.79	$a^2F'_3-a^2G'_4$	71
6.......	3340.33	0	15	35	IIIru	29928.59	$b^4F'_2-a^4F_2$	74
3.......	3337.79	−5	2	2	V	29951.35	$a^2P'_2-b^2F_3$	75
3.......	3336.98	+2	......	tr	....	29958.63	$a^4P'_3-b^2D'_3$	73
6.......	3335.19	+2	20	40	IIIru	29974.71	$b^4F'_3-a^4F_3$	74
6.......	3332.10	0	8	30	Vr	30002.50	$b^4P'_3-a^4S'_2$	76
6.......	3329.45	0	20	70	IIIru	30026.39	$b^4F'_4-a^4F_4$	74
6.......	3326.76	+1	5	20	IIIru	30050.66	$b^4F'_2-a^4F_3$	74
6.......	3322.93	+1	20	75	IIIru	30085.29	$b^4F'_5-a^4F_5$	74
6.......	3321.70	+1	6	25	IVr	30096.44	$b^4P'_2-a^4S'_2$	76
3.......	3319.08	0	......	(1)	....	30120.19	$b^4F'_4-a^2F_3$	77
6.......	3318.01	−1	8	10	IIIru	30129.91	$b^4F'_3-a^4F_4$	74

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multiplet
6.......	3315.32	+1	4	10	V	30154.35	$b^4P'_1-a^4S'_2$	76
6.......	3308.79	−2	8	8	IIIru	30213.86	$b^4F'_4-a^4F_5$	74
3.......	3307.72	0	......	tr	....	30223.64	$b^4F'_3-a^2F_3$	77
3.......	3306.04	+2	......	tr	....	30238.98	$a^4P'_1-a^2P_2$	78
6.......	3302.09	+1	2	0	V	30275.16	$b^4F'_5-a^2F_4$	77
3.......	3298.20	+1	......	(1)	....	30310.87	$a^4P'_1-a^2P_1$	78
6.......	3288.58	0	3	5	IV	30399.53	$b^4P'_2-b^4D'_1$	79
6.......	3288.42	0	2	5	V	30401.02	$b^4P'_3-b^4D'_2$	79
6.......	3288.13	−1	3	on	IV	30403.71	$b^4F'_4-a^2F_4$	77
6.......	3287.64	−1	10	40	Vr	30408.24	$b^2G_4-a^2H_5$	80
3.......	3286.78	0	......	0..	....	30416.18	$b^2G_5-a^2H_5$	80
6.......	3282.32	−1	8	25	Vr	30457.51	$b^4P'_1-b^4D'_1$	79
6.......	3279.98	+1	3	4	V	30479.23	$a^2G_4-b^2D'_3$	81
6.......	3278.91	0	15	35	Vr	30489.18	$a^2D_3-b^2D'_2$	82
6.......	3278.28	0	10	30	Vr	30495.04	$b^4P'_2-b^4D'_2$	79
11.......	3276.98	−1	......	tr	....	30507.14	$b^4F'_3-a^2F_4$	77
6.......	3276.76	+1	4	5	V	30509.18	$a^4P'_3-a^4S'_2$	83
6.......	3275.28	0	2	3	V	30522.97	$a^2D_2-b^2D'_2$	82
6.......	3272.06	−1	10	25	Vr	30553.01	$b^4P'_1-b^4D'_2$	79
6.......	3271.63	0	10	25	Vr	30557.02	$b^4P'_3-b^4D'_3$	79
3.......	3269.75	+3	......	(1)	....	30574.59	$a^2P'_1-b^4D'_2$	84
3.......	3266.41	0	......	(1)	....	30605.85	$a^2P'_2-b^4D'_3$	84
6.......	3263.68	+1	2	4	V	30631.44	$a^4P'_2-a^4S'_2$	83
6*......	3261.59	{−1 0}	25	60	Vr	30651.09	$b^2G_5-a^2H_6$ $b^4P'_2-b^4D'_3$	80 79
6†......	3260.26	0	3	3	III	30663.59	$a^4P'_1-a^4S'_2$	83
6.......	3254.23	0	20	30	IIIr	30720.41	$a^4F'_5-a^4F_4$	85
6.......	3252.85	−2	25	40	IIIr	30733.43	$a^4F'_4-a^4F_3$	85
6.......	3251.89	+1	20	30	IIIr	30742.51	$a^4F'_3-a^4F_2$	85
6.......	3249.37	+1	2	2	V	30766.34	$a^2D_2-b^2D'_3$	82
6.......	3248.60	0	15	50	IIIr	30773.63	$b^4P'_3-b^4D'_4$	79
6.......	3241.97	−1	40	60	IIIr	30836.58	$a^4F'_2-a^4F_2$	85
3.......	3240.72	+1	......	1	....	30848.48	$b^4F'_2-a^2D'_2$	86
6.......	3239.65	0	8	30	Vr	30858.65	$a^2D_3-a^2P_2$	87
6.......	3239.03	+2	40	60	IIIr	30864.56	$a^4F'_3-a^4F_3$	85
6.......	3236.57	+1	50	70	IIIr	30888.02	$a^4F'_4-a^4F_4$	85
6.......	3236.10	−1	8	20	Vr	30892.50	$a^2D_2-a^2P_2$	87
6.......	3234.52	+1	60	75	IIIr	30907.60	$a^4F'_5-a^4F_5$	85
6.......	3232.26	−1	8	30	IVru	30929.21	$a^2G_4-b^2F_3$	88
6.......	3231.30	−1	6	4	III	30938.40	$b^4F'_4-a^2D'_3$	86
6.......	3229.40	0	10	35	Vru	30956.59	$a^2G_5-b^2F_4$	88
6.......	3229.18	0	15	40	IIIr	30958.70	$a^4F'_2-a^4F_3$	85
6.......	3228.59	−2	10	30	Vr	30964.37	$a^2D_2-a^2P_1$	87
6.......	3226.76	+1	5	2	IV	30981.92	$a^4F'_4-a^2F_3$	89
6.......	3224.23	−1	8	35	Vru	31006.23	$a^2H'_6-b^2G'_5$	90
6.......	3222.82	−1	15	35	IIIr	31019.79	$a^4F'_3-a^4F_4$	85
3.......	3220.48	−7	......	1	....	31042.34	$b^4F'_3-a^2D'_3$	86
6.......	3218.25	−1	8	25	IVru	31063.84	$a^2H'_5-b^2G'_4$	90
6.......	3217.04	−1	15	30	IIIr	31075.52	$a^4F'_4-a^4F_5$	85
6.......	3214.76	0	6	4	IV	31097.57	$a^4F'_5-a^2F_4$	89
3.......	3214.12	+2	......	1	....	31103.76	$a^2H'_5-b^2G'_5$	90
12.......	3213.59	−2	......	tr	....	31108.88	$a^4F_5-c^4F'_4$	91
6†......	3213.14	+3	8	1	III	31113.25	$a^4F'_3-a^2F_3$	89
3.......	3208.6	+4	......	1n	....	31157.27	$a^4F_4-c^4F'_3$	91

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multi-plet
3	3206.00	0	......	1	......	31182.54	$a^2D_3-b^2F_3$	92
6	3203.42	−2	4	3	IV	31207.65	$a^4F'_2-a^2F_3$	89
6	3202.52	−1	12	40	Vr	31216.42	$a^2D_2-b^2F_3$	92
6	3197.51	0	4	2	IV	31265.32	$a^4F'_4-a^2F_4$	89
12	3195.99	+1	......	tr	......	31280.20	$a^4P'_3-b^4D'_4$	93
6	3195.71	+1	2	3	V	31282.93	$a^2D_3-a^4S'_2$	94
3	3194.77	......	......	6n?	......	31292.13	......	......
3	3194.55	−10	......	8n?	......	31294.29	$a^4F_5-c^4F'_5$	91
3	3194.25	−13	......	5n?	......	31297.23	$a^4F_4-c^4F'_4$	91
3	3192.67	−2	......	4n	......	31312.71	$a^4F_3-c^4F'_3$	91
12	3192.26	+1	......	2	......	31316.73	$a^2D_2-a^4S'_2$	94
6	3190.87	+1	20	30	IVr	31330.39	$a^2D_3-b^2F_4$	92
3	3189.52	−1	......	5n	......	31343.64	$a^4F_2-c^4F'_2$	91
12	3184.09	−2	......	2	......	31397.09	$a^4F'_3-a^2F_4$	89
3	3182.57	−4	......	6n	......	31412.09	$a^2D'_2-c^2F'_3$	95
3	3181.82	−2	......	8n	......	31419.50	$a^2D'_3-c^2F'_4$	95
3	3180.23	−5	......	2n	......	31435.20	$a^4F_2-c^4F'_3$	91
3	3178.62	−2	......	3n	......	31451.12	$a^4F_3-c^4F'_4$	91
3	3175.67	3	......	2n	......	31480.34	$a^4F_4-c^4F'_5$	91
3	3174.81	......	......	5	......	31488.86	......	......
6	3168.52	+1	30	40	IIIru	31551.37	$b^4F'_5-a^4D'_4$	96
3	3164.89	......	......	8	......	31587.56	......	......
6	3162.56	−1	25	35	IIIru	31610.82	$b^4F'_4-a^4D'_3$	96
6	3161.76	−1	20	30	IIIru	31618.83	$b^4F'_3-a^4D'_2$	96
6	3161.19	−1	20	25	IIIru	31624.53	$b^4F'_2-a^4D'_1$	96
6	3157.39	0	2	2	IV	31662.59	$a^4F'_3-a^2D'_2$	97
6	3155.65	−2	10	12	IVru	31680.05	$b^4F'_4-a^4D'_4$	96
6	3154.18	−3	10	12	IVru	31694.81	$b^4F'_2-a^4D'_2$	96
6	3152.24	−2	12	15	IVru	31714.31	$b^4F'_3-a^4D'_3$	96
6	3148.03	−2	12	12	IV	31756.73	$a^4F'_2-a^2D'_2$	97
12	3145.38	0	......	0	(V)	31783.48	$a^2S_1-c^2P_1$	98
6	3144.72	0	2	1	V	31790.14	$a^2S_1-c^2P_2$	98
6	3143.75	+1	10	10	IV	31799.94	$a^4F'_4-a^2D'_3$	97
3	3136.75	+4	......	tr	......	31870.92	$a^2D_2-b^4D'_3$	99
7†	3130.81	+2	15?	15	IV	31931.39	$a^4F'_3-a^2D'_3$	97
6†	3128.64	+4	8	10n	IV	31953.53	$a^2F_4-c^2F'_4$	100
7†	3127.90	−3	5	10n	IV	31961.09	$a^2F_3-c^2F'_3$	100
7	3122.10	+3	......	2	......	32020.47	$a^2P'_2-a^4P_1$	101
6	3121.60	−1	2	1	V	32025.60	$a^4F'_2-a^2D'_3$	97
3	3119.80	0	5	15	V	32044.07	$b^4P'_3-a^4P_2$	102
3	3118.85	+3	......	2	......	32053.83	$a^2D_3-b^4D'_4$	99
6	3117.66	−1	8	20	V	32066.07	$b^4P'_2-a^4P_1$	102
3	3115.09	+4	......	1	......	32092.52	$a^2P'_2-a^4P_2$	101
6	3112.05	0	3	10	V	32123.87	$b^4P'_1-a^4P_1$	102
7	3110.61	+4	4	20	IV	32138.74	$b^4P'_2-a^4P_2$	102
3	3110.11	+4	......	8	......	32143.90	$b^2D_3-c^2D'_3$	103
3	3108.93	+5	......	0	......	32156.10	$b^2D_3-c^2D'_2$	103
6	3106.23	0	10	35	Vr	32184.07	$b^4P'_3-a^4P_3$	102
6	3105.08	0	5	20	Vr	32195.97	$b^4P'_1-a^4P_2$	102
3	3104.60	+3	......	3	......	32200.94	$b^2G_4-c^2F_4$	104
6	3103.80	0	6	50	Vr	32209.25	$b^2G_5-c^2F_4$	104
3	3103.00	+4	......	2	......	32217.56	$a^2P'_1-a^4P_2$	101
3	3097.63	+2	......	1	......	32273.40	$b^2D_2-c^2D'_3$	103
6	3097.18	0	7	25	Vr	32278.09	$b^4P'_2-a^4P_3$	102

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multiplet
3	3096.43	+1	......	2	....	32285.90	$b^2D_2-c^2D'_2$	103
12	3090.04	+7	......	8n	....	32352.82	$a^4G'_6-c^4F'_5$	105
6	3089.39	+1	6	15	Vr	32359.48	$b^2G_4-c^2F_3$	104
6	3088.03	+1	60	75	IIIr	32373.72	$a^4F'_5-a^4D'_4$	106
3	3081.58	0	......	5n	....	32441.48	$a^4G'_5-c^4F'_4$	105
6	3078.64	0	45	50	IIIr	32472.47	$a^4F'_4-a^4D'_3$	106
6	3075.22	0	40	40	IIIr	32508.58	$a^4F'_3-a^4D'_2$	106
6	3072.97	0	40	40	IIIr	32532.38	$a^4F'_2-a^4D'_1$	106
12	3072.54	−1	......	(on)	....	32536.93	$a^4G'_4-c^4F'_3$	105
6	3072.10	0	30	30	IIIr	32541.59	$a^4F'_4-a^4D'_4$	106
6	3071.23	0	4	15	V	32550.80	$a^4P'_3-a^4P_2$	107
6	3066.52	+2	3	3	IVr	32600.81	$a^4P'_2-a^4P_1$	107
6	3066.36	0	20	20	IVr	32602.50	$a^4F'_2-a^4D'_2$	106
6	3066.20	−2	30	30	IVr	32604.21	$a^4F'_3-a^4D'_3$	106
6	3063.48	−1	2	4	V	32633.16	$a^4P'_1-a^4P_1$	107
3	3063.26	+1	......	2	....	32635.50	$a^4G'_3-c^4F'_2$	105
6*	3059.73	0 −1	5	6 4	IV	32673.13	$a^4P'_2-a^4P_2$ $a^4F'_3-a^4D'_4$	107 106
6	3058.08	0	7	50	Vru	32690.77	$a^4P'_3-a^4P_3$	107
11	3057.43	+2	......	10	....	32697.73	$a^4F'_2-a^4D'_3$	106
6	3056.74	0	4	15	V	32705.10	$a^4P'_1-a^4P_2$	107
6	3048.77	+1	1	6	V	32790.61	$b^2D_3-b^2P_2$	108
6	3046.67	−1	5	30	V	32813.20	$a^4P'_2-a^4P_3$	107
3	3045.10	......	......	5n	....	32830.11	....	......
6	3043.85	+5	1	5	V	32843.60	$b^2D_2-b^2P_1$	108
3	3038.71	−2	......	6	....	32899.15	$a^2H'_6-a^2H_5$	109
3	3036.78	+1	......	1	....	32920.04	$b^2D_2-b^2P_2$	108
6	3029.72	0	4	35	V	32996.77	$a^2H'_5-a^2H_5$	109
3	3023.88	+3	......	12	....	33060.49	$a^2G'_4-c^2G_4$	110
3	3022.83	+4	......	15	....	33071.97	$a^2G'_5-c^2G_5$	110
6	3017.18	−1	4	50	Vru	33133.91	$a^2H'_6-a^2H_6$	109
3	3008.33	+2	......	2	....	33231.38	$a^2H'_5-a^2H_6$	109
3†	2995.75	......	4	5	IV	33370.96	....	......
3	2990.15	−2	......	10	....	33433.41	$a^2D'_3-d^2F'_4$	111
3	2987.38	+1	......	1	....	33464.41	$a^2D_3-a^4P_3$	112
3	2979.18	−3	......	10	....	33556.52	$a^2D'_2-d^2F'_3$	111
3	2977.78	......	......	7	....	33572.29	....	......
3	2958.98	0	......	50	....	33785.59	$a^2G'_4-b^2H'_5$	113
3	2958.28	−2	......	2	....	33793.59	$a^4F_5-a^4G_5$	114
3	2954.76	0	......	60	....	33833.84	$a^2G'_5-b^2H'_6$	113
3	2952.10	−3	......	4	....	33864.32	$a^4F_4-a^4G_4$	114
3	2945.47	+1	......	50	....	33940.57	$a^4F_5-a^4G_6$	114
3	2943.12	2	......	12n	....	33967.65	$a^2F_4-d^2F'_4$	115
6§	2941.99	0	......	50	....	33980.69	$a^4F_4-a^4G_5$	114
3	2941.39	......	......	8n	....	33987.63	....	......
3	2938.69	0	......	30	....	34018.84	$a^4F_3-a^4G_4$	114
3	2936.17	1	......	30	....	34048.05	$a^4F_2-a^4G_3$	114
3	2931.27	+3	......	40	....	34104.96	$a^2F_3-d^2F'_3$	115
3	2928.69	......	......	15	....	34135.01	....	......
3	2927.87	3	......	2n	....	34144.57	$a^4F_5-a^4H'_6$	116
3	2926.75	1	......	10	....	34157.62	$a^4F_5-d^2F'_4$	117
6	2924.01	......	2	8	V	34189.63	....	......
12	2923.65	0	......	tr	....	34193.83	$a^4F_4-a^4H'_5$	116
12	2920.79	−11	......	on	....	34227.32	$a^4F_3-a^4H'_4$	116

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multiplet
3	2918.77	+2	...	2n	...	34251.01	$a^2F_3-d^2F'_4$	115
3	2916.70	−5	...	1	...	34275.31	$c^2D_3-d^2F_4$	118
3	2916.09	...	...	10	...	34282.48	...	...
3	2914.89	...	...	10	...	34305.78	...	...
3	2913.34	...	...	10	...	34314.85	...	...
10	2913.08	0	...	1	...	34317.91	$a^4F'_4-a^2G'_4$	119
3	2910.76	−2	...	0n	...	34345.26	$a^4F_4-d^2F'_4$	117
6	2909.91	0	1	7	V	34355.29	$a^4F'_5-a^2G'_5$	119
3	2909.45	−2	...	1n	...	34360.73	$c^2D_2-d^2F_3$	118
3	2908.14	...	...	4n	...	34376.21	...	...
3	2906.69	...	...	20	...	34393.34	...	...
3	2901.94	−2	...	0	...	34449.63	$a^4F'_3-a^2G'_4$	119
3	2895.81	+4	...	tr	...	34522.56	$a^4F'_4-a^2G'_5$	119
6	2891.05	−1	3	15	V	34579.40	$a^2F'_4-b^2D'_3$	120
3	2890.59	...	...	8n	...	34584.90	...	...
6	2888.92	−1	2	15	V	34604.89	$a^2F'_3-b^2D'_2$	120
3	2888.62	...	...	10n	...	34608.48	...	...
6	2887.46	+2	1	2	V	34622.39	$a^2G_5-b^2G'_4$	121
6	2884.10	+1	7	70	V	34662.72	$a^2G_5-b^2G'_5$	121
3‡	2880.28	0	...	3	...	34708.70	$b^2D_3-c^2F_4$	122
6	2877.42	−1	6	60	V	34743.18	$a^2G_4-b^2G'_4$	121
3	2875.79	...	...	10n	...	34762.88	...	...
3	2875.39	...	...	15n	...	34767.73	...	...
3‡	2874.08	−2	...	2	...	34783.55	$a^2G_4-b^2G'_5$	121
3	2870.04	...	...	25n	...	34832.53	...	...
6	2868.73	−1	2	15	V	34848.42	$a^2F'_3-b^2D'_3$	120
3	2868.29	−1	...	0n	...	34853.78	$a^4G'_6-a^4G_5$	123
6	2862.31	−1	4	30	V	34926.59	$a^2P'_2-c^2D'_3$	124
3	2861.99	...	...	20n	...	34930.49	...	...
6	2861.29	−1	1	3	V	34939.04	$a^2P'_2-c^2D'_2$	124
3	2860.79	...	...	4n	...	34945.14	...	...
6	2858.40	0	1	8	V	34974.35	$a^2F'_3-a^2P_2$	125
3	2857.79	...	...	15	...	34981.82	...	...
3	2856.62	+2	...	2	...	34996.16	$b^2D_2-c^2F_3$	122
3	2856.24	+1	...	25	...	35000.81	$a^4G'_6-a^4G_6$	123
3	2855.49	−4	...	1n	...	35010.00	$a^4G'_5-a^4G_4$	123
6	2853.92	0	2	10	V	35029.26	$a^2F'_4-b^2F_3$	126
6	2851.09	−1	2	20	V	35064.02	$a^2P'_1-c^2D'_2$	124
3	2846.09	+5	...	15	...	35125.62	$a^4G'_5-a^4G_5$	123
3	2844.09	−1	...	2n	...	35150.32	$a^4G'_4-a^4G_3$	123
6	2841.91	−1	7	30	Vr	35177.28	$a^2F'_4-b^2F_4$	126
3‡	2839.70	+4	...	15	...	35204.67	$a^4G'_6-a^4H'_6$	127
3	2836.64	+4	...	15	...	35242.62	$a^4G'_4-a^4G_4$	123
3	2834.14	−2	...	10	...	35273.73	$a^4G'_5-a^4G_6$	123
6	2832.16	−1	5	20	V	35298.37	$a^2F'_3-b^2F_3$	126
3*	2828.89	+1 +1	...	30n	...	35339.19	$a^4G'_3-a^4G_3$ $a^4G'_5-a^4H'_5$	123 127
6	2828.15	0	2	60	V	35348.42	$a^4G'_6-a^4H'_7$	127
3	2827.22	−2	...	10	...	35360.06	$a^4G'_4-a^4G_5$	123
3	2821.41	+3	...	8	...	35432.87	$a^4G'_3-a^4G_4$	123
12	2820.36	...	1	4	V	35446.06	...	...
3	2819.99	−4	...	8	...	35450.71	$a^4G'_4-a^4H'_4$	127
6	2817.84	0	(1)	60	...	35477.76	$a^4G'_5-a^4H'_6$	127
3	2815.57	+2	...	2	...	35506.35	$a^4P'_2-c^2D'_3$	128

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multiplet
3	2814.61	+ 5	......	tr	....	35518.46	$a^4P'_2-c^2D'_2$	128
3	2812.05	+ 2	......	1	....	35550.80	$a^4P'_1-c^2D'_2$	128
6	2810.28	− 2	1	50	V	35573.19	$a^4G'_4-a^4H'_5$	127
6	2806.41	− 2	1	5	V	35622.23	$a^2P'_1-b^2P_1$	129
3	2805.01	+ 3	(tr)	40	....	35640.01	$a^4G'_3-a^4H'_4$	127
3	2800.65	+ 2	......	30	....	35695.50	$a^4F_5-a^4D_4$	130
3	2790.62	+ 2	......	3n	....	35823.79	$a^4F_4-a^4D_3$	130
3	2788.00	+ 3	......	8	....	35857.46	$a^4F_3-a^4D_2$	130
3	2785.99	− 2	......	6n	....	35883.32	$a^4F_4-a^4D_4$	130
3	2784.67	+ 3	......	3	....	35900.32	$a^2F'_4-b^4D'_4$	131
3	2782.30	0	......	2n	....	35930.91	$a^4F_2-a^4D_1$	130
3	2780.55	− 2	......	5n	....	35953.51	$a^2F'_3-b^4D'_3$	131
3*	2778.48	− 3 −10	......	2n	....	35980.31	$a^4F_2-a^4D_2$ $a^4F_3-a^4D_3$	130 130
3	2768.20	− 4	......	tr	....	36113.91	$a^2F_4-c^2G_4$	132
3	2765.65	0	......	0n	....	36147.21	$a^4D'_3-d^4F'_3$	133
3	2765.22	+ 2	......	0	....	36152.83	$a^4P'_2-b^2P_2$	134
3	2764.80	− 1	1	10	V	36158.33	$a^2D_3-c^2D'_3$	135
3	2764.3	+ 2	......	(1)	....	36164.87	$a^4D'_2-d^4F'_2$	133
3	2763.90	− 2	......	(1)	....	36170.08	$a^2F'_3-b^4D'_4$	131
12	2762.92	+ 3	......	(0n)	....	36182.92	$a^4D'_4-d^4F'_4$	133
3	2762.22	− 1	......	2	....	36192.11	$a^2D_2-c^2D'_3$	135
3	2761.29	0	(1)	7	....	36204.28	$a^2D_2-c^2D'_2$	135
3	2758.9	− 3	......	1n	....	36235.64	$a^4D'_1-d^4F'_2$	133
3	2758.35	− 2	......	2n	....	36242.87	$a^4D'_2-d^4F'_3$	133
12	2757.62	0	......	3n	....	36252.47	$a^4D'_3-d^4F'_4$	133
3	2752.85	− 7	......	4n	....	36315.27	$a^4D'_4-d^4F'_5$	133
3	2751.70	− 3	......	50n	....	36330.45	$a^2F_4-c^2G_5$	132
3	2746.70	+ 1	......	30n	....	36396.58	$a^2F_3-c^2G_4$	132
3†	2742.30	......	15	8n	III	36454.99	....	......
3	2738.7	0	......	3n	....	36502.90	$b^2P'_2-c^2P_2$	136
3*	2730.95	− 6	(tr)	6n?	....	36606.47	$b^2P'_1-c^2P_1$	136
3	2725.78	+ 1	(tr)	3	....	36675.91	$a^2G_4-a^2H_5$	137
3	2719.39	+ 2	(tr)	2	....	36762.09	$a^2D_2-b^2P_1$	138
3	2717.29	− 1	(tr)	3	....	36790.49	$a^2G_5-a^2H_6$	137
3	2716.20	− 5	(tr)	4	....	36805.24	$a^2D_3-b^2P_2$	138
3	2713.76	+ 1	......	(1)	....	36838.34	$a^2D_2-b^2P_2$	138
3	2707.05	0	......	0	....	36929.65	$b^2P'_2-d^2D'_3$	139
3	2698.52	......	......	30	....	37046.38	....	......
3	2695.97	− 4	......	0	....	37081.42	$b^2P'_1-d^2D'_2$	139
3*	2655.30	− 1 + 1	......	tr	....	37649.35	$a^2P'_2-c^2F_3$ $a^4F_5-d^4F'_4$	140 141
3	2646.08	− 1	......	50n	....	37780.52	$a^4F_5-d^4F'_5$	141
3	2642.15	0	(tr)	20n	....	37836.71	$a^4F_4-d^4F'_4$	141
3	2638.70	+ 2	......	10n	....	37886.18	$a^4F_3-d^4F'_3$	141
3	2635.60	+ 3	......	5n	....	37930.74	$a^4F_2-d^4F'_2$	141
3‖	2632.95	− 8	......	tr	....	37968.92	$a^4F_4-d^4F'_5$	141
3	2630.2	0	......	tr	....	38008.61	$a^4F_2-d^4F'_3$	141
3	2604.11	+ 2	......	(2)	....	38389.39	$b^4F'_4-b^2D'_3$	142
3	2581.73	+ 3	......	1	....	38722.15	$a^2D_3-c^2F_4$	143
3*	2573.91	− 1 − 1	......	tr	....	38839.79	$b^4F'_4-b^2F_3$ $a^4G'_6-d^4F'_5$	144 145
3	2573.72	+ 3	......	0	....	38842.65	$a^2F'_4-b^2G'_4$	146
7	2572.63	......	......	5	....	38859.11	....	......

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multiplet
7	2571.03	+1	(1)	20		38883.29	$a^2F'_4-b^2G'_5$	146
3	2568.98	+3		1		38914.31	$a^2D_2-c^2F_3$	143
3	2564.49	−1		1		38982.44	$a^4G'_5-d^4F'_4$	145
3	2555.98	0	(tr)	10		39112.22	$a^2F'_3-b^2G'_4$	146
3	2548.71	−3		tr		39223.77	$a^4G'_3-d^4F'_2$	145
3	2546.88	−4		tr		39251.96	$a^4F'_4-b^2D'_3$	147
7	2535.87	0	(1)	10		39422.36	$b^4F'_2-b^4D'_1$	148
7	2534.62	+1	(2)	20		39441.80	$b^4F'_3-b^4D'_2$	148
7	2531.25	+2	(2)	20		39494.31	$b^4F'_4-b^4D'_3$	148
3†	2529.86	+12		0		39516.00	$b^4F'_2-b^4D'_2$	148
3	2525.60	+1	(1)	30		39582.65	$b^4F'_5-b^4D'_4$	148
7	2524.63	+1	(tr)	8		39597.86	$b^4F'_3-b^4D'_3$	148
3	2519.79	−1		0		39673.92	$b^4F'_2-b^4D'_3$	148
3	2519.31	0		0		39681.48	$a^4F'_5-b^2F_4$	149
3	2518.06	+1		2		39701.17	$a^4F'_4-b^2F_3$	149
7	2517.43	0		2		39711.12	$b^4F'_4-b^4D'_4$	148
3	2510.90	+1		2		39814.38	$b^4F'_3-b^4D'_4$	148
3	2498.94	−1		(2)		40004.91	$a^2F'_4-c^2D'_3$	150
3	2481.49	0		(1)		40286.23	$a^2F'_3-c^2D'_2$	150
10	2478.77	−1		(1)		40330.41	$a^4F'_2-b^4D'_1$	151
3‖	2478.64	−4	(tr)	(5)		40332.52	$a^4F'_3-b^4D'_2$	151
3	2477.21	+3		(2)		40355.81	$a^4F'_4-b^4D'_3$	151
3	2474.22	+4		(2)		40404.58	$a^4F'_5-b^4D'_4$	151
3	2469.15	+2		(1)		40487.53	$a^4F'_3-b^4D'_3$	151
3	2464.00	+5		(1)		40572.15	$a^4F'_4-b^4D'_4$	151
12	2450.44	+1	(tr)	(6)		40796.64	$b^2D_3-d^2D'_3$	152
3	2447.92	−1		(2)		40838.64	$b^2D_3-d^2D'_2$	152
3	2442.67	−2		(2)		40926.39	$b^2D_2-d^2D'_3$	152
3	2440.21	+2	(tr)	(5)		40967.67	$b^2D_2-d^2D'_2$	152
3	2357.82	0		(2)		42399.07	$b^4P'_2-c^4D'_1$	153
3	2355.86	−1		(1)		42434.35	$b^4P'_3-c^4D'_2$	153
3	2355.17	0		(2)		42446.79	$b^4P'_3-c^4D'_3$	153
3	2354.61	0		(1)		42456.86	$b^4P'_1-c^4D'_1$	153
3	2354.12			(3)		42465.71		
3	2350.67	+1		(2)		42528.04	$b^4P'_2-c^4D'_2$	153
3	2349.97	0		(3)		42540.69	$b^4P'_2-c^4D'_3$	153
3	2347.46	−1		(2)		42586.21	$b^4P'_1-c^4D'_2$	153
3	2346.35	0		(1)		42606.33	$b^4P'_3-c^4D'_4$	153
3	2342.31			(3)		42679.81		
3	2341.23			(3)		42699.49		
3	2334.54			(3)		42821.82		
3	2291.85	0		(1)		43619.40	$a^2D_2-c^4D'_1$	154
3	2286.23	+3		(1)		43726.62	$a^2D_3-c^4D'_3$	154
3	2269.14	+1		(3)		44055.91	$b^2G_4-d^2F_3$	155
3	2265.13	+2		(1)		44133.90	$c^2D_3-e^2D'_2$	156
3	2261.64	+1		(1)		44201.98	$b^2G_4-d^2F_4$	155
3	2261.23	+1		(3)		44210.01	$b^2G_5-d^2F_4$	155
3	2253.26	−2		(2)		44366.37	$c^2D_2-e^2D'_2$	156
3	2250.09	+1		(2)		44428.85	$c^2D_3-e^2D'_3$	156
3	2238.39	−1		(1)		44661.07	$c^2D_2-e^2D'_3$	156
7	2231.04			(2)		44808.18		
3	2230.95	+3		(1)		44809.98	$a^2D_3-d^2D'_3$	157
3	2229.25	+1		(1)		44844.18	$a^2D_2-d^2D'_3$	157
3	2228.85	+1		(1)		44852.21	$a^2D_3-d^2D'_2$	157

TABLE II—*Continued*

Source	Obs. λ (I.A.)	Δλ O−C	Int. Arc	Int. Spark	Temp. Class	ν	Designation	Multi-plet
3.......	2227.14	−2	......	(2)	....	44886.64	$a^2D_2-d^2D'_2$	157
12.......	2201.31	0	......	(1)	....	45413.27	$c^2D_3-e^2F_3$	158
3.......	2190.13	0	......	(1)	....	45645.08	$c^2D_2-e^2F_3$	158
3.......	2187.50	0	......	(1)	....	45699.95	$c^2D_3-e^2F_4$	158
12.......	2162.68	0	......	(4)	....	46224.36	$b^4P'_3-b^4P_2$	159
12.......	2159.50	0	......	(3)	....	46292.42	$b^4P'_2-b^4P_1$	159
12.......	2159.09	0	......	(5)	....	46301.21	$b^4P'_3-b^4P_3$	159
12.......	2158.29	−1	......	(2)	....	46318.57	$b^4P'_2-b^4P_2$	159
12.......	2156.80	0	......	(1)	....	46350.36	$b^4P'_1-b^4P_1$	159
12.......	2155.58	−2	......	(4)	....	46376.59	$b^4P'_1-b^4P_2$	159
12.......	2154.70	−2	......	(4)	....	46395.53	$b^4P'_2-b^4P_3$	159
12.......	2139.25	+2	......	(0)	....	46730.57	$a^4P'_3-b^4P_2$	160
12.......	2135.73	+1	......	(1)	....	46807.57	$a^4P'_3-b^4P_3$	160
12.......	2134.84	+1	......	(0)	....	46827.09	$a^4P'_2-b^4P_1$	160
12.......	2133.63	−1	......	(00)	....	46853.64	$a^4P'_2-b^4P_2$	160
12.......	2133.36	−1	......	(0)	....	46859.57	$a^4P'_1-b^4P_1$	160
12.......	2132.20	+2	......	(0)	....	46885.06	$a^4P'_1-b^4P_2$	160
12.......	2130.15	0	......	(1)	....	46930.18	$a^4P'_2-b^4P_3$	160
12.......	2104.37	−2	......	(1)	....	47505.03	$a^2D_3-b^4P_2$	161
12.......	2101.28	0	......	(0)	....	47574.88	$a^2F'_4-c^4D'_3$	162
12.......	2054.54	+1	......	(3)	....	48657.04	$a^2F'_4-d^2D'_3$	163
12.......	2043.26	+3	......	tr	....	48925.62	$a^2F'_3-d^2D'_3$	163
12.......	2041.49	0	......	(3)	....	48968.03	$a^2F'_3-d^2D'_2$	163
8.......	1914.11	+9	......	(00)	....	52243.6	$a^4F'_4-c^4D'_3$	164
8.......	1911.01	+5	......	(0)	....	52328.4	$a^4F'_2-c^4D'_1$	164
8.......	1909.74	+11	......	(2)	....	52363.1	$a^4F'_3-c^4D'_2$	164
8.......	1909.33	+11	......	(2)	....	52374.4	$a^4F'_3-c^4D'_3$	164
8.......	1908.29	+10	......	(3)	....	52402.9	$a^4F'_4-c^4D'_4$	164
8.......	1906.30	+5	......	(3)	....	52457.7	$a^4F'_2-c^4D'_2$	164

NOTES TO TABLE II

Source

1. Crew, *Astrophysical Journal*, **60**, 108, 1924.
2. Eder und Valenta, in Kayser, *Handbuch der Spectroscopie*, **6**, 655, 1912.
3. Exner and Haschek, *ibid.*
4. Fiebig, *ibid.*
5. Hasselberg, *ibid.*
6. Kilby, *Astrophysical Journal*, **30**, 243, 1909.
7. King, *Mt. Wilson Contr.*, No. 274; *Astrophysical Journal*, **59**, 155, 1924, and unpublished material.
8. Lang, unpublished material.
9. Lohse, in Kayser, *Handbuch der Spectroscopie*, **6**, 655, 1912.
10. Miss Moore, unpublished material.
11. Rowland, in Kayser, *Handbuch der Spectroscopie*, **6**, 655, 1912.
12. Russell, unpublished material.

* Blend.

† Arc Blend.

‡ Error in λ corrected.

§ Strong reversed spark line coincides with arc line.

|| Displaced by blend.

TABLE II*a*

LINES MASKING LINES OF *Ti* II

λ(I.A.)	Element	ν	Designation	Multiplet
4655.70	*Ti*	21473.06	$a^4P'_1-a^4F_2$	18
4629.34	*Ti*	21595.33	$a^4P'_3-a^4F_4$	18
4549.64	Ti^+	21973.64	$a^4P'_3-a^2F_4$	20
3491.05	Ti^+	28636.51	$c^2D_2-d^2D'_2$	59
3361.00	*Ti*	29744.53	$b^4P'_2-a^2P_1$	69
3354.64	*Ti*	29800.92	$b^4P'_1-a^2P_1$	69
3252.85	Ti^+	30733.43	$a^2D_3-b^2D'_3$	82
3248.60	Ti^+	30773.63	$b^4F'_3-a^2D'_2$	86
3234.52	Ti^+	30907.60	$a^4P'_3-b^4D'_2$	93
3218.25	Ti^+	31063.84	$a^4P'_3-b^4D'_3$	93
2810.28	Ti^+	35573.19	$a^2P'_2-b^2P_2$	129
2631.33	Fe^+	37992.27	$a^4F_3-d^4F'_4$	141
2555.98	Ti^+	39112.22	$a^4G'_4-d^4F'_3$	145

For the next level, b^4F', with excitation potential[1] 0.15 volt, the strongest lines are of class III and those of medium intensity often of class IV, and the faintest ones of class V—appearing in the arc but not in the furnace. For a^2F' (0.60 volt) the strong lines are of class IV and reversed in the spark, and the weaker ones of class V. Next come a^2D and a^2G (1.08 and 1.12 volts), for which the strongest lines are of class V; a few of them are reversed in the spark, while the weaker components of the multiplets appear in the spark alone. Substantially the same statement is true of all the following terms from a^4P' (1.18 volts) to b^2G (1.88), but the proportion of the fainter lines which appear in the arc at all tends to diminish. For b^2P' (2.05 volts) only the stronger lines appear in the arc, and the higher terms, b^2F' (2.58), a^2S (2.63), and c^2D (3.10) give very few lines which are not confined to the spark. Finally, the lines corresponding to transitions upward from the odd triad a^4D', a^4F, a^4G', and the corresponding doublet terms, for which the excitation potential ranges from 3.73 to 4.28 volts, though some of them are very strong in the spark, appear as mere traces, if at all, in heavy exposures to the arc.

[1] This term is to be understood here, as in the writer's "List of Ultimate and Penultimate Lines," as defining the energy required to raise an atom to the state in which it can absorb the lines in question. This is obviously the quantity which is of astrophysical importance. The excitation potential for emission of a line depends on the higher energy state involved and is much greater.

Temperature classification, therefore, is quite as important in analyzing a spark spectrum as it is for an arc spectrum. Additional stages in the classification—VI, VII, and so on—would be required to take care of the lines which appear feebly or not at all in the arc, and still further steps, based on a study of other sources, would lead up to more lines which appear only in the vacuum spark. The spectrum of titanium, which, in an easily observable region, contains lines of all degrees of difficulty of excitation up to the very refractory lines of *Ti* IV, would furnish excellent material for such an investigation.

6. ZEEMAN EFFECT

The magnetic resolutions of many titanium lines have been measured by King[1] and by Babcock (unpublished). A comparison of their results with the predictions of Landé's theory[2] is given in Table III. The first column gives the terms involved (without regard to which is at the higher energy-level); the second, the wave-length of the line; and the third and fourth, the observed displacements of the p and n components in the usual units. Babcock's values are distinguished by being given to three decimal places. When there are several p or n components, the strongest is printed in heavy type. The letters "w_1," "w_2," "w_3" denote numerically greater degrees of widening of an unresolved group of components.

The fifth and sixth columns give the theoretical pattern. When many close components are present, some of the intermediate ones are omitted, but the strongest ones are always given. The last two columns give the blended pattern which is likely to be observed when the group cannot be resolved. In deriving this, it has been assumed that the center of the unresolved group will appear to be one-fourth of the way from the strongest line toward the weakest. This rule closely approximates the results obtained by weighting the lines in proportion to their theoretical intensities.[3] In practice, it appears to represent about what is observed for a line of moderate intensity. For strong lines, the effective mean position may be expected, for

[1] *Publications of the Carnegie Institution of Washington*, No. 153, 36–43, 1912.

[2] *Zeitschrift für Physik*, **15**, 189, 1923.

[3] H. Hönl, *Zeitschrift für Physik*, **31**, 340, 1925.

TABLE III

ZEEMAN PATTERNS FOR *Ti* II

Terms	λ	Observed		Theory*		Blend	
		p	*n*	*p*	*n*	*p*	*n*
$^2S_1-{}^2P_1$.......	4780	0.699	1.353	0.67	1.33		
$^2S_1-{}^2P_2$.......	4805	.347	**0.993**	.33	**1.00**		
			1.70		1.67		
$^2P_1-{}^2P_1'$.......	4316	0	0.671	.00	0.67		
$^2P_1-{}^2P_2'$.......	4330	.271	**1.479**	.33	1.00		
					1.67		
$^2P_2-{}^2P_2'$.......	4350	0	1.26	.00	1.33		
		0.185					
$^2P_1-{}^2D_2$.......	4873	?	0.87	.07	0.73	0	0.84
	4563	0	.81		**.87**		
$^2P_2-{}^2D_2$.......	4590	0.84	0.48	.27	0.53	0.66w	1.03w
			1.05	**.80**	**1.07**		
			1.60		1.60		
	4421	.33	1.12w				
	3706	0.62	$0.90w_1$				
$^2P_2-{}^2D_3$.......	4911	w_1	1.10	.07	**1.00**	0	1.10
	4533	w_1	$1.011w_1$	**.20**	1.13		
	4374	0	1.022		1.26		
					1.40		
$^2D_2-{}^2D_2'$.......	5226	0	0.804	.00	0.80		
	5010	0	.86				
	4337	0	.810				
	3757	0	0.86				
$^2D_2-{}^2D_3'$.......	4344	0.182	1.443	**.20**	0.60	w	1.50w
		0.597	1.875	.60	1.00		
	4287	w_3	$1.72w_2$		1.40		
	3776	w_1	1.45		**1.80**		
$^2D_3-{}^2D_3'$.......	5188	0	1.202	.00	1.20		
	5072	0	1.20				
	4294	0	1.220				
	3741	0	1.15				
$^2D_2-{}^2F_3$.......	5381	0	0.936	**.03**	0.77	0	0.90
	4443	0	.923	0.09	.83		
	4411	0	.887		.89		
	4171	0	0.89		**0.94**		

* The theoretical patterns given in the fifth and sixth columns and the computed blends in the last two columns apply equally to all of the lines having the same multiplet designation as indicated in the first column. Leaders in the fifth and sixth columns indicate the omission of one or more components from the theoretical pattern.

TABLE III—*Continued*

Terms	λ	Observed *p*	Observed *n*	Theory* *p*	Theory* *n*	Blend *p*	Blend *n*
${}^2D_3-{}^2F_3$	4450	0.82	1.20	0.17	0.34	0.69	1.03
				.51	0.69		
				.86	**1.03**		
					1.37		
					1.71		
${}^2D_3-{}^2F_4$	5336	0	1.086	**.03**	**1.00**	0	1.07
	4488	0	1.072	.09	1.06		
	4395	0	1.079	.14	....		
	4163	0	1.04		1.29		
${}^2D_3-{}^2F_4$ / ${}^2D_2-{}^2F_3$	3685	0	1.05			0	1.00
${}^2F_3-{}^2F'_3$	3761.3	0	0.90	.00	0.86		
	3748	0	0.83				
${}^2F_3-{}^2F'_4$	3721	w_2	1.53	**.14**	0.43	w	1.50 w
				.43	....		
				.71	1.57		
					1.86		
${}^2F_4-{}^2F'_4$	3759	0	1.25	0.00	1.14		
	3761.8	0	1.10				
${}^2F_3-{}^2G_4$	4501	0	0.910	**.02**	0.80	0	0.93
	4386	0	.934	.05	.84		
	4053	0	0.87	.08	....		
					.97		
${}^2F_4-{}^2G_4$	4444	0.76	$0.98w_2$	.13	0.25	0.70w	1.02w
				.38	....		
				.63	**1.02**		
				.89	....		
					1.78		
${}^2F_4-{}^2G_5$				**.02**	**1.00**	0	1.05
	4468	0	1.050	.05	1.03		
	4367	0	1.047	.08	....		
	4028	0	1.02	.11	1.22		
${}^2G_4-{}^2G'_4$	5185	0	0.886	0	0.89		
${}^2G_5-{}^2G'_5$	5129	0	1.145	0	1.11		
${}^2G_4-{}^2H_5$	4572	0	0.94	**0.01**	0.84	0	0.95
				.03	.86		
				....	....		
				0.07	**0.98**		

TABLE III—*Continued*

Terms	λ	Observed		Theory*		Blend	
		p	*n*	*p*	*n*	*p*	*n*
$^2G_5-{}^2H_5$......	4529	$0.83w_1$	$1.07w_2$	0.10 .30 .50 .71 **.91**	0.20 .... **1.01** 1.82	0.71w	1.01w
$^2G_5-{}^2H_6$......	4549	0	1.051	**.01** .03 .... 0.09	**1.00** 1.02 .... 1.18	0	1.04
$^4P_1-{}^4D_1$......	4314	1.308	1.304	1.33	1.33		
$^4P_1-{}^4D_2$......	4398 4301	0.71 .717	0.46 .500	0.73	**0.47** 1.93		
$^4P_2-{}^4D_1$......	4320	.845	0.861 2.586	.87	0.87 **2.60**		
$^4P_2-{}^4D_2$......	4409 4307	.78 0.773	? 0.942 1.478 1.976	.27 **.80**	0.93 **1.47** 2.00		
$^4P_2-{}^4D_3$......	4290	w_3	$0.95w_2$	**.18** .54	**0.83** 1.19 1.55 1.91	w	1.10w
$^4P_3-{}^4D_2$......	4330	w_3	$2.14w_2$	**.20** .60	1.00 1.40 1.80 **2.20**	w	1.90w
$^4P_3-{}^4D_3$......	4409 4312	0.54 0.52	1.65 1.48	.11 .34 **.57**	1.03 1.26 **1.48** 1.71 1.94	0.46w	1.48w
$^4P_3-{}^4D_4$......	4395 4300	w_1 $0w_2$	1.18 $1.157w_2$	**.09** .26 .43	**1.00** 1.17 .... 1.86	w	1.21w
$^4P_1-{}^2D_2$......	4568 4464	0.86 0.88	? 0.00 1.68	.93	0.13 **1.73**		
$^4P_2-{}^2D_2$......	4470	1.40	0.39 1.18 2.22	0.47 **1.40**	0.33 **1.27** 2.20		

TABLE III—*Continued*

Terms	λ	Observed		Theory*		Blend	
		p	n	p	n	p	n
$^4P_2-{}^2D_3$......	4417	**0.263** .797	**0.356** .731 0.923 1.464	**0.27** .80	**0.40** 0.93 1.47 2.00		
$^2P_1-{}^4D_2$......	4394	.225	1.451	.27	0.93 **1.47**		
$^2P_2-{}^4D_2$......	4418	0.253	1.275	.07 **.20**	1.13 **1.27** 1.40	0.17	1.27
$^2P_2-{}^4D_3$......	4399	0	1.383	**.02** .06	1.32 1.35 1.39 **1.43**	0	1.40
$^2D_3-{}^4D'_3$......	4173	0.34	1.27	.09 .26 **.43**	0.94 1.11 **1.29** 1.46 1.63	0.35	1.29
$^2D_3-{}^4D'_4$......	4161	w_2	1.75w_2	**.11** .34 .57	0.86 .... 1.77 **2.00**	0w	1.72w
$^2F_3-{}^4F'_2$......	3814	w_2	1.34	**.23** .69	0.63 1.08 **1.54**	0w	1.31w
$^2F_4-{}^4F'_3$......	3836	w_1	1.42	**.06** .17 .28	0.86 0.97 .... **1.43**	0w	1.29w
$^2F_4-{}^4F'_4$......	3813	w_1	1.22	.05 .14 .24 **.33**	0.90 .... **1.19** 1.48	0w	1.19w
$^2F_3-{}^4G_3$......	4012	0.64	0.75w_2	.14 .43 **.71**	0.14 .43 **0.71** 1.00 1.29	0.64w	0.71w
$^2F_4-{}^4G_4$......	4025	0.49	1.00	.08 .24 .40 **0.56**	0.59 .... **1.06** 1.54	0.48w	1.06w

obvious reasons, to be nearer the weakest component, and for weak lines, nearer the strongest.

The agreement between the observed and computed separations is, in almost all cases, within the error of observation. It affords what is probably the most comprehensive test of Landé's formulae for the case of a doublet system that can at present be made. The agreement is also excellent for the two quartet multiplets, and for the intercombinations, many of which show unusual and interesting Zeeman patterns. Further observations, especially in the ultra-violet, would be of value. The unresolved pair at λ 3685 would be especially interesting; but very high resolving power would be required to separate the components. The observed resolution agrees tolerably with the anticipated blend. The line λ 4417 shows an *n* component at 0.731, which is not accounted for, and probably belongs to some neighboring line.

The only real discordances are for λλ 4330 ($b^2P'_1-a^2P_2$), 4350 ($b^2P'_2-a^2P_2$), and 4421 ($b^2P'_2-b^2D'_2$). The observations of the first and third are complicated by adjacent lines; but it appears probable that the g values for a^2P_2 and $b^2D'_2$ are abnormal. These two terms have the same inner-quantum number and closely adjacent energy-levels, and may perturb one another, as in the case studied by Back[1] in calcium. The intensities of some of the combinations involving these terms are abnormal; for example, $b^2D_2-a^2P_2$ and $a^2D_3-b^2D'_2$ are the strongest lines in the corresponding multiplets, though they should be weak. The assumption that $g=1.21$ for a^2P_2 (instead of 1.33) gives the patterns (0.27), 0.93, **1.48** for λ 4330, and (0.07, **0.19**), 1.14, **1.27**, 1.40 for λ 4350.

The unresolved pattern for λ 4421 suggests that $b^2D'_2$ has a g value about 1.0 instead of 0.80; but the data are insufficient for a determination.

7. THEORETICAL INTERPRETATION OF THE OBSERVED TERMS

Hund's theory[2] of the relation of spectral lines to electronic configurations in the atom finds an admirable confirmation in this

[1] *Zeitschrift für Physik*, **33**, 579, 1925.

[2] *Ibid.*, p. 345; **34**, 296, 1925.

spectrum. In the first long period, the orbits[1] of lowest total quantum number which the valency electron can occupy are 4s, 4p, 3d, and 4f. From general considerations based on our knowledge of other spectra it appears that the 3d and 4s electrons will be bound most closely, and almost equally so, and next the 4p's, while the 4f's will be much more loosely held. The atomic configurations of lowest energy will therefore involve only 3d and 4s electrons, and will give rise to terms of the "even" set—S, P′, D, F′, etc. These terms will not combine with one another, but will combine freely with higher-lying "odd" terms S′, P, D′, F, etc., arising from configurations containing one 4p electron. These again will combine with still higher even terms, corresponding to configurations in which one of the electrons is raised to a 5s or 4d orbit. Configurations containing more highly excited electrons, or two 4p orbits, or a 4f orbit, are likely to have such high energy as to give rise either to faint lines or to lines in the Schumann region.

The lines which are to be expected from the various electronic configurations are given in Table IV. The groups of terms which should arise from the addition of a third electron to each of the spectroscopic terms of *Ti* III[2] corresponding to a given arrangement of the first two electrons are listed separately; thus the addition of a 4p electron to the configuration which gives the $^3F'$ term of *Ti* III (the normal state of the corresponding ion) gives triads of D′, F, G′ terms in the quartet and doublet systems. The electron which is supposed then to be added is the last in order in the configuration given in the first column. For the configurations $(3d)^3$, where Pauli's restriction is operative, such an assignment of the terms to particular terms in *Ti* III is impracticable.

The observed terms which are believed to correspond to the various predictions of theory are given in the last column of Table IV. In some instances the identifications are immediate; thus the term a^2H' belongs to the same set as the lowest terms in the atom and is evidently even; and it can be assigned only to the configuration $(3d)^3$. Similarly, a^2S, which is also low and even, must belong to $(3d)^2 4s$,

[1] The use of this convenient term indicates no dissent from the later "wave" theory.

[2] *Mt. Wilson Contr.*, No. 337; *Astrophysical Journal*, **66**, 25, 1927.

and the odd terms a^4S', a^4G', a^2H to $(3d)^2 4p$, in the positions in which they are placed.

TABLE IV

PREDICTED AND OBSERVED TERMS IN *Ti* II

Configuration	Limit in *Ti* III	Predicted Terms	Observed Terms
$(3d)^3$.	. . . .	$^4P'$, $^4F'$,	a^4P', b^4F'
		$^2P'$, ^2D, $^2F'$; ^2G, $^2H'$, ^2D	a^2P', b^2D, b^2F'; a^2G, a^2H', —
$(3d)^2 4s$	a^3P'	$^4P'$	b^4P'
		$^2P'$	b^2P'
	a^3F'	$^4F'$	a^4F'
		$^2F'$	a^2F'
	a^1S	^2S	a^2S
	a^1D	^2D	a^2D
	a^1G	^2G	b^2G
$3d(4s)^2$.	a^3D, b^1D	^2D	c^2D
$(3d)^2 4p$.	a^3P'	$^4S'$, ^4P, $^4D'$	a^4S', a^4P, b^4D'
		$^2S'$, ^2P, $^2D'$	a^2S', b^2P, c^2D'
	a^3F'	$^4D'$, ^4F, $^4G'$	a^4D', a^4F, a^4G'
		$^2D'$, ^2F, $^2G'$	a^2D', a^2F, a^2G'
	a^1S	^2P	. . . .
	a^1D	^2P, $^2D'$, ^2F	a^2P, b^2D', b^2F
	a^1G	^2F, $^2G'$, ^2H	c^2F, b^2G', a^2H
$3d\cdot 4s\cdot 4p$. . . .	a^3D	^4P, $^4D'$, ^4F	b^4P, c^4D', —
		^2P, $^2D'$, ^2F	c^2P, d^2D', d^2F
	b^1D	^2P, $^2D'$, ^2F	—, e^2D', e^2F
$(3d)^2 5s$.	a^3P'	$^4P'$	. . . .
		$^2P'$	. . . .
	a^3F'	$^4F'$	c^4F'
		$^2F'$	c^2F'
	a^1S	^2S	. . . .
	a^1D	^2D	. . . .
	a^1G	^2G	. . . .
$(3d)^2 4d$.	a^3P'	$^4P'$, ^4D, $^4F'$	—, —, —
		$^2P'$, ^2D, $^2F'$	—, —, —
	a^3F'	$^4P'$, ^4D, $^4F'$, ^4G, $^4H'$	—, a^4D, d^4F', a^4G, a^4H'
		$^2P'$, ^2D, $^2F'$, ^2G, $^2H'$	—, —, d^2F', c^2G, b^2H'
	a^1S	^2D	. . . .
	a^1D	^2S, $^2P'$, ^2D, $^2F'$, ^2G	—, —, —, —, —
	a^1G	^2D, $^2F'$, ^2G, $^2H'$, ^2I	—, —, —, —, —

In most cases, however, alternative possibilities are open, and further evidence is needed for the assignment. This can be obtained in several ways: (*a*) The terms formed by the addition of a p electron to a given term of the "parent spectrum" of the next highest

degree of ionization form triads (except when the parent term is an S term). The terms of a given triad usually, though not always, lie at about the same level. (*b*) The terms which are produced by adding another electron to the arrangement corresponding to a given parent term combine with one another to give strong multiplets, while combinations with terms of different parentage usually give much weaker lines. The reason for this is evident; in the first case a single electron "jumps" without any rearrangement in the rest of the atom; in the second, more or less rearrangement takes place, which is statistically much less probable. (*c*) If the electron jump increases the azimuthal quantum number l (e.g., from an s to a p orbit), the multiplet in which the azimuthal quantum number L increases will be the strongest (e.g., the transition from F to G) and that in which it decreases, the weakest (F to D). But if the electron decreases its l, the opposite is the case. This rule was communicated to the writer by Dr. Otto Laporte. Like the preceding one, it is an obvious consequence of the correspondence principle. (*d*) Terms produced by adding an electron of a given kind (e.g., 4p) to various parent terms are usually, though not always, situated at about the same relative levels as the parent terms.

The parent terms in *Ti* III, with their relative levels (measuring upward from the lowest level, and taking the component of highest inner-quantum number), are:

$(3d)^2$		$3d \cdot 4s$	
a^3F_4'	422	a^3D_3	38,425
a^1D_2	8473	b^1D_2	41,704
a^3P_2'	10,721		
a^1S_0	14,053?		
a^1G_4	14,398		

As for the strength of the combinations, Table V gives the estimated intensity of the strongest line in each of the multiplets resulting from the combination of the terms which head the corresponding row and column, and provides the necessary data.

Beginning with the quartet terms of *Ti* II, we find obvious triads of odd terms, a^4D', a^4F, a^4G' and a^4S', a^4P, b^4D', which evidently belong to $(3d)^2 4p$ and are produced by the addition of a 4p electron to a^3F' and a^3P', respectively. The average term values for the two

TABLE V

Line Intensities *Ti* II

d^2p	ds^2	d^2s							d^3							$d^2 \cdot d$							$d^2 \cdot s$	
	c^2D	b^4P'	a^4F'	a^2S	b^2P'	a^2D	a^2F'	b^2G	a^4P'	b^4F'	a^2P'	b^2D	b^2F'	a^2G	a^2H'	a^4D	d^4F'	a^4G	a^4H'	d^2F'	c^2G	b^2H'	c^4F'	c^2F'
a^4S'	.....	30r				3			5															
a^4P	.....	35r		(1)		1			50ru		2													
b^4D'	.....	50r	(4)			2	5n		tr	30	(1)	3					(0)							
a^4D'	.....	2	75r			1	60		60	40ru	35	tr					4n			.....	.....	.....	1n	
a^4F	.....		75r			tr	4		(1)	75ru				tr		30	50n	50	2n	10			8n?	
a^4G'	.....		125r			(2)	4			30ru				tr			1	25	60	.....	.....	.....	8	
a^2S'	.....	(1)		(1)	2	0			6		100													
b^2P	0	.....	.....		20	4			0		5	6	(1)											
c^2D'	2	.....	.....		40	10	(2)		2		30	8	40											
a^2P	*i*	2		(1)	1	30r	8		tr		8	20												
b^2D'	*i*		(1)		1	35r	15		1	(2)	8	50ru		4										
b^2F	(1)		2			40r	30r	7		tr*	2	60	1	35ru	(0)									
a^2D'	*i*	tr	12		(2)	50	250r		40	4	30	6	*i*	1		.....	.....	.....	.....	10			.....	8n
a^2F	*i*	tr	4			60	200r		(1)	0	tr	4	*i*	50		.....	.....	.....	.....	40	50n		.....	10n
a^2G'	.....		7				75r	2	.....	.....			*i*	70	60n	.....	.....	.....	.....		15	60	.....	4n
c^2F	15	.....	.....			1		50r	.....	.....	tr*	3	15											
b^2G'	.....	.....	.....				20	80r	.....	.....			15	70	35ru									
a^2H	.....	.....	.....					40r	.....	.....				3	50ru									
dsp																								
b^4P	.....	(5)				(1)			(1)															
c^4D'	(ou)	(3)	(3)			(1)	(0)																	
c^2P	(0)	.....	.....	1	3n																			
d^2D'	tr	.....	.....		0	(2)	(3)		.....	.....		(6)												
d^2F	1	.....	.....					(3)																
e^2D'	(2)																							
e^2F	(1)																							

* = Blend *i* = Too far to red.

triads are (roughly) 31,400 and 41,000; their difference is 9600, while $a^3P' - a^3F'$ is 10,300. The two remaining odd quartet terms, b^4P and c^4D', may be assigned with confidence to the triad of origin $3d \cdot 4s \cdot 4p$. Their mean level, 54,400, is 23,000 higher than that of the lowest triad, while a^3D is 38,000 higher than a^3F', but this difference is not beyond the limits of probability. The multiplet $a^4F' - c^4D'$ was found near λ 1900 in a list of lines measured by Professor Lang. The ^4F term, which should give another but fainter multiplet near by, could not be identified.

Of the pair of low $^4F'$ terms, one must arise from $(3d)^3$ and the other from $(3d)^2 4s$; and the same is true of the $^4P'$ terms. It appears from Table V that a^4F' gives a stronger combination with a^4G' than with a^4D', and b^4F' the contrary; hence the former must be assigned to $(3d)^2 4s$ and the latter to $(3d)^3$. In the case of the $^4P'$ terms, the situation is reversed; the higher one, b^4P', combines strongly with b^4D', while the combination from the lower one gives very faint lines. The resulting assignment is confirmed by the fact that b^4P' gives a strong multiplet with b^4P, and a^4P' a weak one. In the former case the transition is from the configuration $(3d)^2 4s$ to $3d \cdot 4s \cdot 4p$, and involves only the jump of a single electron; in the latter the transition is from $(3d)^3$, involving a double electron jump.

Of the high even quartet terms, a^4H' and a^4G can arise only from $(3d)^2 4d$. These terms combine strongly with the triad a^4D', a^4F, a^4G', and so must belong to the parent term a^3F. There can be no doubt that a^4D and the two high $^4F'$ terms also belong to this sub-group, the former and one of the latter arising from $(3d)^2 4d$, and the other $^4F'$ term from $(3d)^2 5s$. Since an electron jump from p to d usually gives stronger lines than one from p to s, the term d^4F', which gives the stronger multiplets, may be assigned to the first configuration, and c^4F' to the second. This is confirmed by the fact that c^4F' combines most strongly with the G' term of the triad, and d^4F' with the F term. The latter is what might be expected in combinations between a triad and a pentad of terms of common origin, as has recently been shown in *Sc* II.[1]

All the known quartet terms have now been accounted for. The

[1] Russell and Meggers, *Scientific Papers of the Bureau of Standards*, **22**, 329 (No 558), 1927.

low even terms are theoretically complete, and all but one of the intermediate odd terms have been found. Of the high even terms, only those derived from the lowest parent terms in *Ti* III have been detected, and, of these, one member of the pentad is missing—it should give the faintest combinations of the five. The terms derived from the other terms of *Ti* III might be expected to give fainter combinations, and it is not surprising that they have not been detected.

The numerous doublet terms present a more complicated problem. Among the odd terms, however, three conspicuous triads are present, each of which combines with one of the low even terms to give strong reversed lines, thus: a^2D', a^2F, a^2G' combine with a^2F'; a^2P, b^2D', b^2F with a^2D; and c^2F, b^2G', a^2H with b^2G. This makes it evident that each of these groups arises from a common parent term in *Ti* III; and these must evidently be a^3F', a^1D, and a^1G, the low terms being of origin $(3d)^2 4s$ and the others coming from $(3d)^2 4p$. Only three more levels remain below 50,000; these are a^2S', b^2P, and c^2D', which fit the requirements of the fourth triad, of origin $(3d)^2 4p$ and parent term a^3P'. The mean levels of the leading components of these four triads are 32,755, 39,718, 45,719, and 42,627. Subtracting the levels of the parent terms in *Ti* III, we find 32,333, 31,246, 31,321, and 31,906—a striking confirmation of rule (*d*).

The remaining odd terms, c^2P, d^2D', d^2F; e^2D', e^2F, fall naturally into place as a complete and incomplete triad arising from $3d \cdot 4s \cdot 4p$, though the assignment—and even the reality—of c^2P is somewhat doubtful. The rest of the low even terms are now easy to place. The term a^2S must be assigned to $(3d)^2 4s$. Of the terms a^2P', b^2P', the former combines most strongly with the first member of the triad a^2S', b^2P, c^2D', and the latter with the last. This assigns b^2P' to $(3d)^2 4s$ and a^2P' to $(3d)^3$. The remaining low even terms must arise from $(3d)^3$ or $3d(4s)^2$. Of these c^2D, which lies at the highest level and combines strongly with e^2D', e^2F, may be assigned with confidence to the latter configuration. It is noteworthy that this term combines more strongly with the higher triad of origin $3d \cdot 4s \cdot 4p$, than with the lower one, and that this is also the case in *Sc* I. The remaining doublet terms go by default to $(3d)^3$. As may be seen from Table V, the intensities of their combinations with the odd

terms are in general less than for the terms of origin $(3d)^2 4s$ and are more irregular.

The few even high doublet terms which are known combine with the triad of parentage a^3F' and obviously arise from the configurations $(3d)^2 5s$ and $(3d)^2 4d$. As in the case of the quartets, there are two F' terms, of which the lower one, giving the weaker combinations, may be assigned to $(3d)^2 5s$.

All the known terms of *Ti* II are now accounted for theoretically. Conversely, all the low (even) terms which theory predicts have been found with the exception of one ^2D term of origin $(3d)^3$. Among the middle (odd) terms of origin $(3d)^2 4p$ only one ^2P term is lacking. The parent ^1S term in *Ti* III has been identified very doubtfully, if at all. The missing ^2P and ^4F terms arising from $3d \cdot 4s \cdot 4p$ should give faint multiplets. Of the high even terms, only those arising from the lowest parent term in *Ti* III have been observed, and some of these which should give the weaker combinations are missing.

In all points, therefore, the character of the spectrum is in exact accordance with the predictions of Hund's theory, including the fact that the $^4F'$ terms are lower than the $^4P'$ terms of the same origin, and that the quartet F' and P' terms are lower than the doublets which have the same parent term in *Ti* III.

8. SERIES AND IONIZATION POTENTIAL

According to the interpretation just given, the terms a^4F', c^4F' are successive members of a series, as are also a^2F', c^2F'. The limit of the series should be the lowest term a^3F' of *Ti* III, the components F'_5, $^2F'_4$ going to $a^3F'_4$ as limit; $^4F'_4$, $^2F'_3$ to $a^3F'_3$; and $^4F'_3$, $^4F'_2$ to $a^3F'_2$. Applying a Rydberg formula in the usual manner, determining the height of the limit above the lowest level in *Ti* II, and subtracting the quantities required to reduce all the results to determinations of the difference in level between the normal state of *Ti* II, $a^4F'_2$, and that of *Ti* III, $a^3F'_2$, we find:

Term	$^4F'_5$	$^4F'_4$	$^4F'_3$	$^4F'_2$	$^2F'_4$	$^2F'_3$
Limit	111,874	111,677	111,542	111,448	111,174	110,894
Correction	422	183	0	0	422	183
$a^3F'_2 - a^4F'_2$	111,452	111,494	111,542	111,448	110,752	110,711

The results from the quartet and doublet terms agree quite as well as could be expected. The general mean is 111,233, corresponding to a value of 13.73 volts for the principal ionization potential of *Ti* II—that is, the energy required to pass from the normal state of *Ti* II to that of *Ti* III.

This value is, however, probably slightly too high, for in other cases when a Rydberg formula is applied to the first two terms in a series involving the removal of an s electron, the computed limit is usually higher than that given by a Ritz formula for the whole series.

For a number of spectra in which the ^1S term is the lowest, the percentage excess of the ionization potential calculated from the first two terms of the S series above that derived from the full series is as given below. The ionization potentials for the ionized atoms have been divided by 4 to make them comparable with the others.

Element	*Ba*+	*Sr*+	*Ca*+	*Mg*+	*Cs*	*Rb*	*K*
I/Z^2	2.49	2.74	2.96	3.74	3.88	4.16	4.32
Percentage error	+2.8	+1.4	+1.6	+0.7	+2.0	+1.6	+1.2

Element	*Na*	*Ag*	*Cu*	*Mg*	*Cd*	*Au*	*Zn*	*Hg*
I/Z^2	5.12	7.59	7.69	7.61	8.95	9.20	9.35	10.39
Percentage error	+0.6	+3.0	+2.2	+3.9	+4.7	+3.3	+4.1	+ 5.1

The percentage of error evidently increases with the ionization potential and with the atomic number. From a plot of the data it appears probable that the correction for *Ti* II lies between 1.0 and 1.5 per cent. The round number 110,000 for $a^3F_2' - a^4F_2'$, corresponding to a principal ionization potential of 13.58 volts, is probably as good a value as can at present be adopted.

No previous determination of the quantity has been made by physical methods. By the astrophysical method, based on the behavior of the lines of *Ti* II in stars of different spectral types, Menzel[1] derived the value 12.5 volts—a good approximation, but, like the astrophysical determinations for other elements, a little too low.

The only other series which might be represented among the observed terms in this spectrum involve the configurations $(3d)^3$ and $(3d)^2 4d$ with parent term a^3F' in *Ti* III; but any discussion of

[1] *Harvard Circular*, No. 258, 1924.

these is greatly complicated by the fact that Pauli's restriction operates upon the lower configuration—abolishing a large number of the terms which would otherwise appear and perhaps changing the energy-levels of the others. Of the four known members of the pentad, a^4D, d^4F', a^4G, a^4H', only the second can have a corresponding lower term, which must be b^4F'. Taking the leading components of these terms and referring them to the appropriate limit, $a^3F'_4$, which, with the adopted ionization potential, lies at the height 110,422 above the origin of measurement for *Ti* II, we find the term values for $b^4F'_5$, $d^4F'_5$ to be 109,207 and 41,341, giving the Rydberg denominators 2.004 and 3.257. These values indicate that the two terms are really in series—the lower one being bound with abnormal strength, presumably because it forms part of a "structural" group. This is the case in other spectra; for example, the analogous terms a^3F', b^3F' in *Sc* II give denominators 2.103, 3.284; and an instructive case in *Ti* I will be discussed later.

Among the doublet terms of origin $(3d)^3$ the lowest is a^2G. If this is assumed to belong to the lowest limit, a^3F', it gives a denominator 2.081, while c^2G, which certainly belongs to this limit, gives the denominator 3.209; but whether the two terms are really in series cannot be definitely settled. Higher members of these series may well exist, but they would give lines in the Schumann region.

9. CAUSE OF THE COMPLEXITY OF THE SPECTRUM

In comparing a given spectrum with the spectra of neighboring elements, these may be taken either in the same state of ionization or in the states in which they have the same number of active electrons. In the latter case, the structure of the various spectra is very similar; in the former, the complexity increases rapidly as the incomplete shell of electrons begins to be filled.

The writer and Dr. Meggers[1] have called attention to the great increase in spectral complexity which attends the transition from the one-electron system of *Ca* II to the two-electron system of *Sc* II. In comparing such apparently dissimilar spectra, attention should be fixed, not upon spectroscopic terms, but upon electron jumps. For example, the H and K lines of *Ca* II correspond (in emission)

[1] *Loc. cit.*

to the falling back of a 4p electron into a 4s orbit. The corresponding orbital transition in *Sc* II may be associated with many different arrangements or rearrangements of the other electron orbit, and may give rise, not to 2 lines, but to 36, while the transition from a 4p to a 3d orbit gives 3 lines of *Ca* II and 50 of *Sc* II.

In *Ti* II the complexity is much greater. The electron jump from 4p to 4s, which in *Ca* II gives only two lines—H and K—produces in *Ti* II all the combinations between terms of origin $(3d)^2 4p$ and $(3d)^2 4s$, and also those between groups of origin $3d \cdot 4s \cdot 4p$ and $3d\,(4s)^2$. From the list of terms in Table IV it may be shown without difficulty that the permissible transitions between the terms of the first two groups should give rise, theoretically, to 63 lines belonging to the quartet system, 107 doublet lines, and 150 intercombination lines—a total of 320. The other groups of terms give 20 doublets and 16 intercombinations, so that the whole number of possible lines corresponding to this single electron jump is no less than 356.

The jump from 4p to 3d gives 3 lines in *Ca* II (the infra-red group). In *Ti* II the transition between $(3d)^2 4p$ and $(3d)^3$ should give 73 lines belonging to the quartets, 140 doublets, and 173 intercombinations, while $3d \cdot 4s \cdot 4p$ to $(3d)^2 4s$ accounts for 34 quartets, 56 doublets, and 86 intercombinations—a total of 562 lines.

This computation takes no account of lines corresponding to changes in the "azimuthal" quantum number *L* by more than a unit (such as $^2G - {}^2D$) or of transitions involving a double electron jump, as from $3d \cdot 4s \cdot 4p$ to $(3d)^3$.

When these possibilities—many of which are actually realized—are taken into account, it appears that the possible changes from configurations containing one electron in a 4p orbit to those in which all the valency electrons are in 4s or 3d orbits are capable of producing more than 1000 lines in *Ti* II, as against 5 in *Ca* II. Not all these lines, of course, have actually been observed; most of the intersystem combinations, and many of those between terms of the same system which have different parent terms in *Ti* III, are too faint. It is none the less evident why the observed spectrum is so rich; the electron jump, in this more complex atom, may be accompanied by a great number of different arrangements or rearrangements of the orbits

of the other valency electrons, each giving a different line. It is clear also that, if an atom can do but one thing at a time, the energy which in *Ca* II is concentrated into a few lines must in *Ti* II be distributed over a great many; which explains why there are no enhanced lines of titanium which have the enormous strength of H and K. The strongest lines should be, and are, those in which no rearrangement of the rest of the atom takes place when the electron jumps. The magnitude of the energy change, and hence the wave-length of the line, depends mainly on the nature of the electron jump, so that all these strong lines are crowded together in one part of the spectrum, the near ultra-violet. The leading lines of the multiplets corresponding to the transitions from each of the low terms of origin $(3d)^2 4s$ to the related triad are as follows:

a^4F'....	$\lambda\lambda$ 3349, 3234, 3088	a^2D.....	$\lambda\lambda$ 3190, 3278, 3239
b^4P'....	3248, 3106, 3332	a^2F'.....	3349, 3759, 3685
a^2S.....	3144	b^2G.....	3261, 3505, 3103
b^2P'....	3535, 3456, 4805		

The lines corresponding to an increase in the quantum number (which are the strongest of all) are given first in each row; thus λ 3349 is $a^4F'-a^4G'$, λ 3234 is $a^4F'-a^4F$, and λ 3088 is $a^4F'-a^4D'$.

With the exception of $b^2P'-a^2S'$, all these multiplets lie within a range of 700 A in the near ultra-violet. The principal lines (in the first column) range over less than 400 A.

The jump from 4p to 3d happens, in *Ti* II, to involve the liberation of nearly the same amount of energy as that from 4p to 4s. In *Ca* II and *Sc* II it liberates less; in *V* II and *Cr* II, more. Many of the strong lines arising from such transitions in *Ti* II therefore lie in the near ultra-violet and add to the concentration of strong lines in this region; a minority of these straggle into the violet and blue and account for the lines which are at present of most importance in stellar spectroscopy.

10. COMPARISON OF *Ti* II AND *Sc* I

The arc spectrum of scandium should be similar in general structure to the spark spectrum of titanium, and, since the former has recently been analyzed, it is of interest to compare the two. Quartet and doublet terms arising from similar electronic configurations

have been identified in both, but the relative levels in the two are very different; thus the ^2D term of origin $3d(4s)^2$ is the lowest of all in *Sc* I, and the highest of the basal group in *Ti* II. This, and many differences of like nature, make the detailed structure of the two spectra appear very dissimilar; but the closeness of their actual relationship may be established by means of Moseley's law.

As applied to the optical spectra of elements of different atomic numbers, but with the same number of valency electrons remaining, this law states that the differences of $\sqrt{\nu/R}$ for corresponding spectroscopic terms of successive elements are substantially constant—where R is the Rydberg constant and ν the term value (measured from its own proper limit). This difference, $\Delta\sqrt{\nu/R}$, is almost exactly the same for all the various terms which can be produced by adding an electron of the same sort (e.g., 4p) to different limiting states of the atoms of the next degree of ionization; it is approximately the same for terms involving the addition of electrons of the same total quantum number (4s, 4p, 4d), but it decreases as the total quantum number increases.

Only two of the "three-electron" spectra, *Sc* I, *Ti* II, *V* III, ... , have been analyzed; but the test given in the last sentence is applicable. In applying it, it must be realized that a given term in *Ti* II may be derived in different ways from different terms in *Ti* III. For example, the term b^4P, arising from the configuration $3d \cdot 4s \cdot 4p$, may be produced by the addition of a 3d electron to the configuration $4s \cdot 4p$ of *Ti* III—and, in particular, to the ^3P term arising from this configuration. It may also be produced by the addition of a 4s electron to the ^3P term arising from $3d \cdot 4p$, and of a 4p electron to the ^3D term of origin $3d \cdot 4s$. All three of these terms are known in *Ti* III,[1] and also the corresponding ones in *Sc* II,[2] so that three different values of ν are available for a test.

The identification of the parent terms is unambiguous in this case; but when Pauli's restriction operates, as in the passage from $(3d)^3$ to $(3d)^2$, it is harder to make. Here the terms $^4F'$, $^4P'$, $^2P'$, ^2D,

[1] Russell and Lang, *Mt. Wilson Contr.*, No. 337; *Astrophysical Journal*, **66**, 13, 1927.

[2] Russell and Meggers, *Scientific Papers of the Bureau of Standards*, **22**, 329 (No. 558), 1927.

$^2F'$, ^2G, $^2H'$, ^2D come from $^3F'$, $^3P'$, ^1S, ^1D, ^1G. The quartet terms can arise only from the triplets. It is natural, though not inevitable, to associate $^4F'$ with $^3F'$, and $^4P'$ with $^3P'$, and this is justified in the former case by the series relation discussed in section 8. The associations given below for the doublet terms are uncertain. Similarly, in the transition from $(3d)^2 4s$ ($^4F'$, $^4P'$, ^2S, $^2P'$, ^2D, $^2F'$, ^2G) to $3d\cdot 4s$ (^3D, ^1D), the quartets must go to the triplet terms, and the doublets may go to either. Fortunately, as is shown below by writing out one or two cases, this uncertainty makes very little difference in the value of $\Delta\sqrt{\nu/R}$.

The actual comparison is given in Table VI. The various values of ν are grouped according to the type of electron which is supposed to be removed, and again with respect to the electronic configurations involved.

To save printing, the letters which identify the specific terms and limits of scandium and those for titanium are placed together, separated by a comma; thus in the fourth line the terms a^2F' in *Sc* I and a^2F' in *Ti* II are referred, respectively, to the limits a^1D in *Sc* II and b^1D in *Ti* III.

The components of greatest inner-quantum number have been used in the calculations. In certain cases of ambiguity, when a doublet term has been referred to alternatively possible singlet and triplet limits, the two lines are connected by a bracket. Cases in which the term has not been identified in one of the two spectra, or when the term value cannot be assigned (as is the case for a^4P', a^4P, and a^4S' in *Sc* I, which could not be connected with any other terms), are represented by dashes. Many such terms which have been identified in one spectrum only are omitted to save space. The separations between the extreme components of the terms are given in the last three columns of the table.

It is evident that Moseley's law is very closely satisfied, the only serious discordances being for the two terms marked with colons, for both of which the assignment to the given electronic configuration is doubtful.

Taking means of these differences for the various groups (omitting the doubtful cases), we have the summary in Table VII. The

TABLE VI

COMPARISON OF *Sc* I AND *Ti* II

Electron Removed	Terms	Limits	$\sqrt{\nu/R}$			Separations		
			Sc I	*Ti* II	Diff.	*Sc* I	*Ti* II	Ratio
3d.....	$(3d)^2 4s$	$3d \cdot 4s$						
	a, a^4F'	a, a^3D	0.622	1.158	0.536	157	393	0.40
	a, b^4P'	a, a^3D	....	1.123	....	81	152	.53
	a, a^2F'	a, a^3D	.597	1.144	.547	115	269	.43
	a, a^2F'	a, b^1D	.615	1.157	.542			
	b, a^2D	a, b^1D	.600	1.142	.542	− 12	33	− .36
	a, b^2G	a, b^1D	.581	1.114	.533	− 3	− 8	.37
3d.....	$(3d)^3$	$(3d)^2$						
	b, b^4F'	a, a^3F'	.478	0.998	.520	143	308	.46
	b, a^4P'	a, a^3P'	.519	1.007	.488	80	155	.52
	d, b^2D	b, a^1D	.508:	0.982	.474:	54:	129	.42:
3d.....	$3d \cdot 4s \cdot 4p$	$4s \cdot 4p$						
	a, b^4P	b, b^3P	.826	1.322	.496	67	103	0.65
	a, c^4D'	b, b^3P	.838	1.335	.497	201	161	1.25
	a, c^2P	b, b^3P	.824	1.333:	.509:	145	7:	
	a, d^2D'	b, b^3P	.839	1.332	.493	− 74	− 43	1.72
	a, d^2F	b, b^3P	.812	1.310	.498	53	146	0.36
	b, e^2D'	b, b^3P	.789	1.275	.486	148	295	.50
	b, e^2F	b, b^3P	.785	1.270	.485	140	287	.49
4s.....	$3d(4s)^2$	$3d \cdot 4s$						
	a, c^2D	a, a^3D	.702	1.056	.354	168	232	0.73
	a, c^2D	a, b^1D	.717	1.074	.357			
4s.....	$(3d)^2 4s$	$(3d)^2$						
	a, a^4F'	a, a^3F'	.657	1.003	.346			
	b, a^2D	b, a^1D	.661	1.000	.339			
	a, a^2F'	a, a^3F'	.633	0.981	.348			
	a, b^2G	a, a^1G	.662	0.997	.335			
4s.....	$3d \cdot 4s \cdot 4p$	$3d \cdot 4p$						
	a, b^4P	a, b^3P	.772	1.109	.337			
	a, c^4D'	a, a^3D'	.775	1.110	.335			
	a, c^2P	a, a^1P	.774	1.130:	.356:			
	a, d^2D'	a, a^1D'	.762	1.094	.332			
	a, d^2F	a, a^1F	.770	1.104	.334			
	b, e^2D'	a, a^3D'	.721	1.036	.315			
	b, e^2F	a, a^3F	0.715	1.034	0.319			

TABLE VI—*Continued*

Electron Removed	Terms	Limits	$\sqrt{\nu/R}$			Separations		
			Sc I	*Ti* II	Diff.	*Sc* I	*Ti* II	Ratio
4p.....	3d·4s·4p	3d·4s						
	a, b^4P	a, a^3D	0.569	0.917	0.348			
	a, c^4D′	a, a^3D	.588	.935	.347			
	a, c^2P	a, a^1D	.586	.948:	.362:			
	a, d^2D′	a, a^1D	.608	.946	.338			
	a, d^2F	a, a^1D	.568	.917	.349			
	b, e^2D′	a, a^3D	.516	.848	.332			
	b, e^2F	a, a^3D	.509	.840	.331			
4p.....	$(3d)^2$4p	$(3d)^2$						
	b, a^4D′	a, a^3F′	.489	.841	.352	104	235	0.44
	b, a^4F	a, a^3F′	.502	.849	.347	176	464	.38
	a, a^4G′	a, a^3F′	.520	.855	.335	281	696	.40
	c, a^2D′	a, a^3F′	.480	.846	.366	92	269	.34
	c, a^2F	a, a^3F′	.484	.848	.364	125	283	.44
	a, a^2G′	a, a^3F′	.486	.831	.345	95	205	.46
	a, a^4S′	a, a^3P′	....	.858				
	c, a^4P	a, a^3P′	....	.846	....	87	212	.41
	—, b^4D′	a, a^3P′	....	.854	....	....	235	
	d, a^2P	b, a^1D	.504	.848	.344	− 39	− 71	.55
	d, b^2D′	b, a^1D	.505	.848	.343	105	243	.43
	—, b^2F	b, a^1D	....	.845	....	....	148	
	d, c^2F	a, a^1G	.509	.838	.329	8	−158	− .05
	b, b^2G′	a, a^1G	.513	.858	.345	31	40	.78
	a, a^2H	a, a^1G	.514	.846	.332	96	235	.41
5s.....	$(3d)^2$5s	$(3d)^2$						
	d, c^4F′	a, a^3F′	0.393	0.660	0.267	163	414	0.39

corresponding mean differences for two-electron and one-electron systems are added for comparison.[1]

It is evident that the relations are very regular. The configuration 3d·4s·4p gives somewhat smaller differences than the others. If the results obtained from this configuration, which cannot occur in the two- and one-electron systems, are omitted from the means, the differences become almost identical with those for the simpler atomic systems.

[1] Russell and Lang, *loc. cit.*, supplemented by unpublished studies on *Ca* I.

The separations of the terms in *Sc* I and *Ti* II also show a fairly close parallelism. Out of 27 cases (excluding the two doubtful ones) the ratio of the separations lies between 0.34 and 0.55 in no less than 20. The mean for these is 0.44. The mean ratio of the separations for 13 corresponding triplet terms in *Sc* II and *Ti* III is 0.49 (omitting one discordant case); for three corresponding terms in *Sc* III and *Ti* IV, it is 0.54—a remarkably regular progression.

TABLE VII

MOSELEY'S LAW

Added Electron	3d	4s	4p	5s
Configuration $(3d)^2$	0.504	0.342	0.346	0.267
Configuration 3d·4s	.539	.355	.331	....
Configuration 3d·4p	....	.328	....	....
Configuration 4s·4p	.493	....	....	....
Mean *Ti* II−*Sc* I	.512	.342	.338	.267
Mean *Sc* II−*Ca* I	.551	.351	.351	.265:
Mean *Ca* II−*K* I	0.535	0.369	0.353	0.263

It is worthy of special notice that the inverted terms in *Sc* I and *Ti* II, which are rather numerous, correspond either to inverted terms in the other spectra or to terms of very small separation. Whatever influence is at work to produce the inversion evidently acts in almost the same way in the two cases. All these inverted terms appear to be derived from limits belonging to the singlet systems of *Sc* II or *Ti* III.

There is, however, enough difference between the two spectra to show that the laws which govern the magnitude of the term separations must be rather complicated.

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PHOTOGRAPH OF A REMARKABLE METEOR

By ISSEI YAMAMOTO

ABSTRACT

An *exceptionally bright meteor*, of −14 mag., was observed photographically as well as visually. The path, color, speed, and some other physical characteristics *indicate that it belongs to the Winnecke comet.*

As a part of a program to observe the Pons-Winnecke comet in the present year, the writer made a trip to southern Manchuria and set up a station at Mukden, from June 15 until July 1, 1927. The instruments used were all of small size, ranging from a $1\frac{1}{2}$-inch binocular to a $6\frac{1}{2}$-inch reflecting telescope. Among these a 4-inch clock-driven Zeiss equatorial was very effectively employed. For photographing, a small camera of 2-inch aperture, $f=4$, was attached to the equatorial tube, and the main telescope was used for guiding. The weather was generally fair, and only two nights were completely cloudy. Thirty plates of the comet and twenty-one plates of other objects were taken during the interval. The present expedition was undertaken in order to avoid the rainy season, which occurs annually in the central part of Japan in June and July.

Meteors connected with Winnecke's comet were also watched throughout the interval. These meteors have radiant points which are sometimes quite diffuse, and move from Ursa Major Boötes. They are generally slow and of short path, according to Mr. Denning, who saw them for the first time in 1916. Early in 1921, he appealed to observers of meteors for a careful watch of a probable fine display of the shower in that year.[1] He and some others were somewhat disappointed in the actual apparition, but Mr. Kaname Nakamura, of the Kyoto University Observatory, obtained a fine series of observations of these meteors in June, July, and August, 1921, and beautifully confirmed Denning's prediction.[2] The meteors in 1921 were generally very faint, which caused some other observers to miss them. In the present year, 1927, the earth made an excep-

[1] *Observatory*, **44**, 61, 1921.

[2] I. Yamamoto and K. Nakamura, *Memoirs of the College of Science, Kyoto Imperial University*, **5**, 277, 1922.

tionally close approach to the comet nearly at the time of its perihelion passage, and accordingly a more remarkable display of meteors was expected by some. Mr. K. Nakamura had actually detected the first trains of the expected meteors on June 1, but they remained fairly faint until the end of the month. On June 30, however, through a gap in a cloudy sky, the writer saw several bright meteors radiating from Boötes in an interval, from 21^h0^m to 21^h40^m, Japanese

FIG. 1

Western Standard Time (eight hours in advance of Greenwich time). Among these, one was of +1 mag. and another was of −1. But, on the following nights, the meteors began to fade.

Notwithstanding this, the writer had a rare experience with a meteor observed near midnight on June 29, while making an exposure with the small camera in the Ophiuchus-Scorpio region. The purpose was to photograph the two asteroids Ceres (1) and Parthenope (11), and the exposure began at 23^h33^m. The writer was, as usual, looking into the field of the guiding telescope. At 23^h51^m (15^h51^m U.T.) the surrounding sky suddenly flared up, and immediately the writer

thought it was due to the mischievous act of someone turning a flashlight toward the telescope. In the next moment, a remarkable meteor was noticed in the sky, perhaps in its climax of luminosity. The apparition was low in the southwestern sky, and the meteor was slowly moving downward in the next few seconds. Two or three times the nucleus of the meteor flared up, during the writer's visual watch, which lasted for about three seconds before the disappearance of the phenomenon. The color was reddish yellow. The path was medium to short, and the speed rather slow. A bright streak was left behind, and the immediate surroundings were filled with luminous dustlike matter during the climax of the apparition. These points, together with the track which can be traced backward to the radiant point, are likely to prove the meteor to belong to Winnecke's comet. The maximum light of the meteor was estimated to be about four times as bright as the full moon, so that its stellar magnitude is -14 ± 1.

It was a further surprise to the writer to realize, after a few moments' consideration, that the position of the great meteor was in the central part of the region which he was photographing! The exposure was, according to his program, to end at 23^h56^m, and this was done. After developing, the image of the meteor was found quite satisfactory, and the two asteroids sought are seen on the original negative. The region covered by the plate includes the head of Scorpio, and Antares as well as Saturn are beautifully visible in the picture. In the photograph, the total brightness and the whole length of the track of the great meteor are considerably inferior to the visual impression of the writer, certainly because of the reddish color of the meteor. It is of especial interest that the peculiar nebulosities along the path of the meteor are very well shown; these are characteristic of the Winnecke meteors. Another point of interest is the presence of the three knots of light on the track of the meteor during its fading phase. These knots are images of the successive flarings-up of light which were actually observed visually by the writer. The duration of the whole apparition was estimated visually to be five seconds at least.

A few days afterward, the writer received a letter from Mr. Sh. Sawada, an amateur, who saw the same meteor at Dairen, a city

about 360 km (222 miles) southwest of Mukden. He states that the meteor appeared at a point a little east of Polaris and the altitude was from 40° to 35° approximately. The reported time of apparition is in close agreement with that of the writer. The brilliancy of the meteor was "enormous," outshining all street lights. On consulting a local map, and from a simple triangulation based on track observations at Mukden and Dairen, it is concluded that the meteor flared to its maximum brightness at a height of about 100 km above Hsiung-yo-cheng, a town nearly midway between the two cities, along the South-Manchurian Railway.

KYOTO UNIVERSITY OBSERVATORY
July 12, 1927